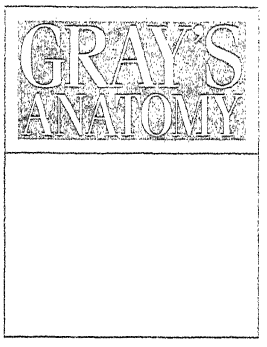


ALIMENTARY SYSTEM

Section Editor: Lawrence H. Bannister

The text on the oral cavity and teeth was extensively revised by Douglas Luke. Contributions on the comparative anatomy of the teeth was by Moya Meredith Smith, on the nasopharyngeal tonsil by Niall Kirkpatrick, on the palatine tonsil by Marta Perry and on oesophageal structure by Bill Owen. Donald Low provided advice on the structure of the gastro-oesophageal orifice. The essay on liver transplantation was provided by D. Mirza and P. McMaster, on pancreatic transplantation by Robert Sells and on hernia and clinical examination by Harold Ellis. My editorial colleagues Giorgio Gabella and Mary Dyson contributed advice and additional material on the enteric microstructure and pancreatic and hepatic anatomy respectively.

INTRODUCTION

This section deals sequentially with the anatomy of the different regions of the human alimentary tract and associated glands. After a consideration of the general features of the tract as a whole, details are given of the initial, rather specialized structures, namely the oral cavity, palatine musculature, salivary glands and teeth, followed by the tongue and pharynx. Next, for convenience, the arrangement of the abdomen and its peritoneal lining are described, before continuing with the oesophagus, stomach, small intestine (duodenum, jejunum, ileum), large intestine (caecum and appendix, colon, rectum), and the anal canal and musculature. Finally, the major abdominal glands, the pancreas and liver (with the gallbladder), are considered. The microscopic anatomy of these structures and relevant aspects of clinical anatomy are described at appropriate points in the text.

General features of the alimentary system

The alimentary system, also described as the digestive or gastrointestinal tract, is by definition primarily concerned with the intake, digestion and absorption of nutrients (alimentation), although it has a number of important accessory functions, e.g. in its upper part it also possesses some respiratory features, since the mouth and parts of the pharynx are shared alimentary and respiratory pathways. Two of its glands, the pancreas and liver, also play more general systemic roles in the body. The anatomical organization of the alimentary system reflects these various activities closely both at the topographic and microscopic levels of organization.

The functions of the alimentary tract, in the context of the process of digestion, are multiple:

- it provides a space for the storage and processing of ingesta, and the elimination of its unabsorbed components (faeces)
- it secretes enzymes and lubricants which process and facilitate the passage of the ingesta
- it absorbs nutrients and other materials and passes them into the body
- it propels material within it by muscular action
- it has defensive, especially immunological, properties
- it houses microorganisms
- its epithelial lining forms a thin but strong barrier between its lumen (a space open to the outside) and the interstitium or true interior of the body.

These functions, together with the structural organization, vascularization, innervation and evolution of the alimentary tract, will be briefly reviewed in this introductory section.

Essentially, the alimentary tract is an epithelium-lined muscular tube capable of selecting then propelling ingested material through a series of different physiological environments created by its secretory and absorptive epithelia. In these compartments, food already broken down mechanically by the teeth is exposed to digestive enzymes which reduce the large biomolecules to components small enough to pass through selective channels in epithelial cell membranes, and thence into the intercellular spaces of the gut wall. Such molecules are then taken into the vascular system for distribution to the body. The undigested remnants within the alimentary lumen are finally eliminated through the anus. As the interior surface of the alimentary tract is continuous at the mouth and anus with the external surface of the body, material within its lumen can be regarded as external to the body, actually entering it only when in the form of small molecules and ions it traverses the cells lining its wall into the surrounding tissues.

The *glands* lining the tract provide the water, enzymes, ionic environments and other attributes required for these purposes. All alimentary glands are epithelial–mesenchymal derivatives; they include large populations of microscopic invaginations of the luminal surface, confined to the alimentary wall. A few are much larger and located mainly outside the tract; these are formed as major diverticula of the tract's epithelial lining, retaining connections in the form of secretory ducts. They comprise the three pairs of major oral salivary glands (parotid, submandibular and sublingual), and the pancreas and liver. The latter two organs have additional functions related to general metabolism as well as to alimentation; the pancreas secretes hormones from specialized endocrine islet cells and the liver carries out a wide range of synthetic and metabolic functions (and in fetal life, haemopoiesis, see p. 187). The control of secretion is carried out by a combination of autonomic nervous, hormonal and local chemical regulation (see p. 1794).

The *motility* of the alimentary canal depends on muscle fasciculi within its wall and, in some regions, also on specialized external muscles which assist or oppose the passage of ingesta. In the mouth and pharynx and at the anus these muscles are largely skeletal in type and under voluntary motor control. Their actions are often quite complex and are precisely co-ordinated; in the mouth and pharynx they are also employed for non-alimentary purposes such as phonation. Throughout most of its extent the alimentary wall contains smooth muscle and is regulated by the autonomic nervous system. In much of the tract the co-ordinated actions of circular and longitudinal muscle layers propel the contents caudally by peristalsis, lubricated by the secretions of the glands in the walls of the tract which also protect the lining against excessive abrasion. Specialized areas of circular muscle form a number of sphincters regulating the passage of substances from one region of the gut to the next; these include the two oesophageal sphincters (upper and lower), and the pyloric and anal sphincters. The control of motility is complex and depends on regional monitoring, in part by sensory nerves connected synaptically to a network of ganglion calls and local motor neurons within the alimentary wall, forming the *enteric nervous system* (p. 1749). Another major controlling influence is the *enteroendocrine system* (p. 1787), a scattered population of peptidergic cells within the lining epithelium which can secrete various peptide hormones from their bases into the subjacent tissues when suitably stimulated by the alimentary contents. Motility is influenced too by circulating hormones, e.g. noradrenalin, products of defensive cells and by extrinsic nervous action, the presiding efferent nerves for most of the tract being the vagus and branches of the thoracolumbar sympathetic system (see pp. 1303–1304).

Alimentation. The breakdown of solid ingested material is begun in the mouth by the mechanical action of the teeth (mastication), the tongue and various neighbouring muscles. These actions greatly increase the surface area of the ingesta and mix them with the secretions of the salivary glands (insalivation). The secretions begin to dissolve soluble substances, promoting their access to taste buds and beginning the digestion of polysaccharides by the action of salivary amylase from the parotid glands. After swallowing (deglutition) by the concerted actions of the tongue, palatine muscles and pharynx, and the rapid transport to the stomach via the oesophagus, gastric digestion proceeds by the action of acidic, protease-rich secretions of multitudes of small gastric glands, which also release intrinsic factor needed for the absorption of iron, and protective mucus. Passing through the pylorus into the first part of the small intestine, the duodenum, the semi-fluid products of gastric digestion encounter alkaline bile from the liver and gallbladder (entering via the bile duct), and pancreatic enzymes from the pancreatic duct. Bile salts physically disrupt liquid masses by detergent action, and the pancreatic secretions contain a wide variety of enzymes capable of hydrolysing many classes of biomolecules. Digestion proceeds throughout the considerable length (up to 6 m) of the small intestine, accompanied by absorption of the resulting small molecules: amino acids, monosaccharides, triglycerides, nucleotides, and of vitamins, etc. by the specialized epithelial cells (enterocytes) lining the small intestine. Enterocytes transport these molecules into the intercellular spaces of the intestinal walls to diffuse into the vascular plexuses lining the alimentary tract. The rate of such movements depends on the surface area of absorptive membrane bordering the intestinal lumen, an area which is quite enormous due to a combination of intestinal length, the considerable folding of its wall and the presence of numerous microvilli on the apices of the absorptive epithelial cells.

The alimentary tract also transports water and electrolytes across its wall; as the enzymes and lubricants are all in aqueous, ionically defined suspensions, large quantities of water and ions, especially sodium and chloride, are released into the tract. These are selectively resorbed (and, in certain cases, exchanged for other ions) through specialized absorptive epithelial cells which are especially numerous in the more caudal parts of the small intestine, the colon and rectum (pp. 1767, 1782). Absorptive cells in the small and large intestines also salvage bile salts and other secreted materials, and absorb

vitamins produced by the symbiotic bacteria in the colon. The large intestine is rich in mucous glands which lubricate the passage of the increasingly solidified faecal material moving through it. Finally, faeces are stored and expelled under voluntary control via the colon, rectum and anal canal, a complex system of sphincters under autonomic and somatomotor control regulating these processes (p. 1781).

Protection of the tract against infection is of course vital because its interior provides an excellent habitat for a diverse bacterial and fungal flora. Although most resident organisms are non-pathogenic if confined to the lumen, and some are important to the body because of their ability to synthesize vitamins, they may cause disease or threaten life if they pass into or through the tract wall. Such populations are normally kept at a harmless level by the secretion of bacteriostatic substances (e.g. lysozyme and lactoferrin) and antibodies (mainly IgA) from glands in its wall. The antibodies are synthesized by congregations of lymphocytes (mucosa-associated lymphoid tissue, MALT: see p. 1442) situated beneath its lining epithelium, and are passed to the epithelial glands for secretion. Other types of lymphocyte and co-operative defensive cells are also numerous within the walls and can combat infectious agents and their toxic products penetrating its lining. Lymphoid tissue is particularly well developed at a number of strategic sites: around the upper end of the pharynx (Waldeyer's ring, p. 1729), at the gastro-oesophageal junction, and in the small intestine (Peyer's patches, pp. 1450, 1771) and appendix; these masses furnish large populations of primed T and B lymphocytes which migrate to and within the surrounding regions.

Barrier functions. Although immunological defence is important, a vital feature of the tract's lining is that it forms a physical barrier to the passage of microorganisms and many potentially harmful substances. The barrier consists of the specialized epithelia lining its lumen. Where considerable abrasion may occur, in the oral cavity, pharynx, oesophagus and anal canal, the epithelia are stratified squamous in type, providing a mechanically protective layer many cells thick. Elsewhere, the epithelium is only one cell thick, but has junctional complexes with tight junctions between cells (p. 1747), preventing diffusion from the lumen into the tissues beneath. The barrier is aided by mucus overlying the epithelium, and by the rapid turnover of epithelial cells which have only a limited lifespan, ensuring that damaged, leaky cells are soon replaced from mitotic stem cells.

Vascular supply and drainage of the alimentary tract

The general pattern of vascularization has already been described in Section 3. Details of the enteric blood system are given in Section 10, and will be reviewed only briefly here. Essentially, the *arterial supply* at both ends of the tract is shared with that of the surrounding regional structures, i.e. in the head and neck, the branches of the external carotid (oral cavity, pharynx), and thyrocervical trunk (cervical oesophagus); in the thorax, it is supplied by segmental arteries from the descending aorta (thoracic oesophagus); most caudally, by branches of the internal iliac (middle rectal artery, inferior rectal branch of the internal pudendal artery) and median sacral artery, which provide blood to the lower two-thirds of the rectum and anal canal. Between these regions, i.e. in the abdomen and pelvic basin, forming the great majority of the tract, there is a very rich blood supply, as might be expected from its secretory and absorptive capabilities. Here, three major median branches from the abdominal aorta serve the three embryonic subdivisions of the gut:

- the coeliac artery to the abdominal part of the foregut (abdominal oesophagus, stomach, and the duodenum as far as the opening(s) of the bile and pancreatic duct)
- the superior mesenteric artery to the midgut (remainder of small intestine and large intestine as far as a point two-thirds along the tranverse colon)
- the inferior mesenteric artery to the hindgut (the rest of the colon and upper third of the rectum).

In the non-abdominal regions of the tract, the *venous drainage* has some similarities with the arterial supply. The alimentary tract in the head and neck are drained by tributaries of the internal jugular vein; in the thorax, the azygos, hemi- and accessory azygos veins, and most caudally, tributaries of the inferior parts of the rectum and anal canal to the internal iliac veins (middle rectal vein; inferior rectal branch of the internal pudendal veins). The majority of the abdominal and pelvic tract has quite a different venous drainage, constituting the hepatic portal system by which nutrients absorbed by the capillary plexuses of the intestines are taken directly to the liver where the veins ramify as a second set of exchange vessels. The main collecting channels of this region are the superior and inferior mesenteric and splenic veins which conjoin as the hepatic portal vein, bifurcating as the paired hepatic veins just before entering the liver. Venous blood from the abdominal oesophagus, stomach, pancreas and gallbladder also drains into this system.

The *lymphatic drainage* of the tract follows similar rules: its parts in the head and neck drain regionally (into the internal jugular lymph trunks); the thoracic oesophagus drains via posterior mediastinal lymph nodes into the thoracic duct, bronchomediastinal trunks and right lymphatic duct (p. 1609). Within the abdomen, the intestine has a rich lymphatic drainage which forms an accessory transport system for the distribution of lipids from their sites of absorption. Lymph is conveyed from the stomach, small and large intestines along lymphatic vessels running parallel with their arteries, to the confluence of abdominal lymphatics and thence to the thoracic duct. This passes the flow of lymph through the thorax to the enter the venous system at the junctions of the left subclavian and internal jugular veins with the left brachiocephalic. Associated with this drainage system are large numbers of mesenteric and related para-aortic lymph nodes (p. 1431), an important line of defence against microorganisms which might enter the circulation by this route.

Nervous supply of the alimentary tract

Motor control of the voluntary skeletal muscles of the oral cavity and pharynx is by the segmental cranial nerves: branchiomotor to most of the musculature (trigeminal, facial, glossopharyngeal, vagal and cranial accessory), and somatomotor to the tongue (hypoglossal). Voluntary muscle of the anal canal is innervated by the somatomotor sacral branches, forming the pudendal nerve. Throughout the tract smooth muscle is regulated by a combination of autonomic efferents:

- parasympathetic via the splanchnic branch of the vagus nerve (all parts of the fore- and mid-gut below the pharynx) and pelvic splanchnic nerves (hindgut)
- sympathetic through the segmental outflow of the thoracolumbar spinal cord (p. 1303) distributed via the sympathetic trunks.

These autonomic inputs are co-ordinated and effected by the enteric nervous system within the wall of the tract (see above, and p. 1749) and receive reflex-mediating afferent branches from the visceral sensory nerves.

The glands of the oral cavity and pharynx are controlled by autonomic nerves, the parasympathetic innervation arising from three cranial nerves: the facial via the pterygopalatine ganglion (all minor glands of the palate) and submandibular ganglion (submandibular and sublingual salivary glands; lingual and buccal glands; possibly a component also to the parotid gland, see p. 1691); the glossopharyngeal via the otic ganglion (mainly the parotid gland); and the vagus (oropharynx, laryngopharynx, pharyngotympanic tube).

The sensory supply of the oral cavity and pharynx comes from general visceral components of cranial nerves V, VII, IX and X; these include chemosensory fibres to the mucosal taste buds of the oral cavity and pharynx, and general sensation to the mucosa. Caudally, the most inferior part of the anal canal is supplied by the sensory nerves of the surrounding structures, that is by the inferior rectal branch of the pudendal nerve, of segmental sacral origin. For the large part of the tract, visceral sensory nerves, chiefly of local segmental origin running with autonomic efferent fibres, monitor the state of the tract, its motility and its mechanical and chemical stresses, perceived consciously mainly as pain, fullness or emptiness, rather imprecisely localized but referred to the particular body segments served by its spinal nerves.

Evolutionary development of the tract

The course of evolution in the alimentary tract can be traced tentatively from comparative vertebrate anatomy and the fossil record. Such studies indicate a common pattern achieved early in the chordate lineage, and which is still clearly visible in the embryonic

development of the human tract and to some extent expressed in its pattern of blood supply and innervation. Throughout chordate evolution the anterior part of the alimentary tract has been associated with the respiratory system (see p. 1628); in the primary aquatic era the two functions appear to have been intimately connected, as they are in extant representatives such as larval lampreys (e.g. *Lampetra*). In such primitive forms, dissolved oxygen and suspended particulate matter are obtained by filtration from the same stream of water, entering through a single opening, the mouth, and sieved through clefts in the walls of the pharynx between branchial arches, the filtered food being passed to a gastrointestinal tract for digestion and absorption. This filter-feeding phase was probably soon superseded by more complex forms of feeding, associated with specialized jaws, teeth and cranial muscles, and the filtering arches were converted into jaws and gills; in such forms, e.g. all modern fishes, the respiratory stream still shares the mouth and pharynx with food. In tetrapods these functions became partially separated with the development of lungs which replaced gills as the major respiratory surfaces, and the system of branchial arches and clefts was converted into a complete buccopharyngeal wall, although the cleft and arch arrangement is still transiently visible in human embryonic development, and its segmental pattern is reflected in the distribution of a number of cranial nerves. The pharyngotympanic tube and middle ear cavity are also relics of a cleft, converted to auditory rather than respiratory purposes in all tetrapods.

In reptiles the separation of the buccal cavity by a partial transverse secondary palatal shelf into a respiratory (nasal) chamber and a true oral cavity allowed a more effective division of the respiratory and alimentary tracts, taken to extremes in the Crocodilia in which the extensive bony secondary palate and a raised larynx allow complete separation of breathing and feeding. A definitive division was achieved in mammals by the growth of horizontal plates from the maxilla and palatine bones to create a rigid hard palate, continuous posteriorly with a movable soft palate capable of sealing off the nasal cavity during swallowing. Some species, e.g. the dog, can elevate the laryngeal opening into the nasopharynx whilst feeding, and this also occurs to some extent during suckling in human infants. In the Cetacea (whales) the position is more extreme, the larynx being permanently inserted into the nasopharynx and quite separate from the alimentary pathway.

The development of hinged jaws and of teeth greatly improved the selection, diminution and ingestion of a wide variety of foodstuffs. It is possible to trace in fossil and modern mammals the elaboration of a complex dentition, and the reduction of the mandibular bones to a single strong tooth-bearing plate articulating with the temporal bone instead of the reptilian quadrate bone, with the incorporation of the latter and some mandibular bones into the auditory apparatus of the middle ear (see p. 1370). Indeed, much of the evolution of the human skull is to be understood in this context, and it can also be speculated that the increased efficiency of food acquisition (and of digestion and assimilation) were prerequisites for many other features needing much chemical energy, for example, the high metabolic rate and homeothermy typical of mammals, and the elaboration of a large brain (neurons having a high demand for circulatory glucose which they are unable to store).

In other parts of the alimentary tract it is also possible to discern evolutionary trends. Its subdivision into an oesophagus, stomach, small and large intestines, with an attendant liver, gallbladder and pancreas appears to be a primitive chordate pattern. Superimposed on this simple arrangement are many variations, often related to specialized diets; for example, in herbivores the breakdown of cellulose requires extensive digestive and absorptive action, assisted by symbiotic organisms within the gut; the stomach is sometimes very elaborate (as in ruminants) and the intestine extensive, frequently having major diverticula. The caecum and vermiform appendix in humans appear to be relics of such a herbivorous past, although now functionless in this respect. The most caudal parts of the alimentary tract have also undergone major changes during evolutionary development. In primitive chordates, alimentary, urinary and genital systems share a common cloacal aperture to the exterior, a condition reflected in human embryonic development (p. 191). The division of the cloaca into separate anal and urinogenital regions, each with its own opening, was probably an adaptation to terrestrial life, occurring first in reptiles; failure to complete this separation during human development is seen in congenital abnormalities such as rectovaginal fistulae.

One other aspect of the alimentary tract must be remarked upon: the origin of important endocrine and defensive structures now quite separate from this structure, but owing an embryonic origin to its epithelial lining. Endocrine derivatives include the thyroid and parathyroid glands and the adenohypophysis; defensive components are the thymus and Waldeyer's ring of lymphoid tissue (p. 1729) comprising the palatine, nasopharyngeal, lingual and tubal tonsils. All of these structures arise during ontogeny from either the buccal cavity or pharynx (p. 176). Their evolutionary origins appear to be from specialized epithelia in the pharynx of lower vertebrates, migrating to a separate site and losing any direct connection to that cavity. In support of this view, among other data, the thyroid of the primitive chordate *Amphioxus* is a specialized patch of epithelial cells on the pharyngeal floor, and in some primitive bony fishes (e.g. *Erpetoichthys*) the adenohypophysis is an open diverticulum of the buccal roof. It can be speculated that the wall of the alimentary tract is an important interface with the outside world which favoured the development of specialized epithelial endocrine and immune control systems.

ORAL CAVITY AND RELATED STRUCTURES

ORAL CAVITY

The oral or buccal cavity, the 'mouth', consists of a narrow *vestibule* outside the teeth, and an inner, larger *oral cavity proper*. The vestibule is bounded externally by the lips and cheeks and internally by gums and teeth, communicating with the exterior by the oral fissure. Above and below, the vestibule is limited by the reflexion of the mucosa from the lips and cheeks on to the gums, forming a horseshoe-shaped trough (the *fornix*). When the teeth are apposed, the vestibule is continuous with the oral cavity proper behind the third molar teeth and by minute clefts between adjacent teeth. The part of the vestibule adjacent to the lips is the *labial sulcus* and the remainder, related to the cheeks, is the *buccal sulcus*. The oral cavity proper (12.1) is bounded at the front and laterally by the alveolar arches, teeth and gums; behind, it communicates with the pharynx at the oropharyngeal isthmus (the space between the palatoglossal folds). Its roof is formed by the hard and soft palates; its floor mainly by the anterior region of the tongue, and the remainder by the mucosa lying on mylohyoid anteriorly and laterally between the base of the tongue and the internal surface of the mandible, on to which it is reflected. The inferior surface of the tongue is connected to the floor of the mouth anteriorly by the lingual frenulum, a crescentic median mucosal fold reinforced by connective tissue. On each side of the lower edge of the frenulum, anteriorly, a small sublingual papilla bears the orifice of the duct of the submandibular salivary gland. From this papilla a ridge extends posterolaterally in the floor, produced by the subjacent sublingual salivary gland and hence termed the sublingual fold. Minute openings of the sublingual gland ducts appear on the edge of the fold.

ORAL MUCOSA

The oral mucosa is continuous with the skin at the labial margins and with the pharyngeal mucosa at the oropharyngeal isthmus. It varies in structure, function and appearance in different regions of the oral cavity and is traditionally divided into three major types

the lining, masticatory and specialized mucosae. The *lining mucosa*, red in colour, covers the soft palate, ventral surface of the tongue, floor of the mouth, alveolar processes excluding the gingivae and the internal surfaces of the lips and cheeks. It has a non-keratinized epithelium overlying a loosely fibrous lamina propria, and the submucosa contains some fat deposits and collections of minor mucous glands. The *masticatory mucosa*, roseate-pink, covers the hard palate and gingivae; it is normally orthokeratinized. A submucosa is absent from the gingivae and the midline palatine raphe, but is present over the rest of the hard palate; it is thick posterolaterally where it contains mucous salivary glands, and also the greater palatine nerves and vessels. The masticatory mucosa is bound firmly to underlying bone or to the necks of the teeth, forming in the gingivae and palatine raphe a *mucoperiosteum*. Where a substantial thickness of submucosa exists in the palate, longitudinal collagenous septa orientated anteroposteriorly anchor the mucosa to the periosteum of the maxillae and palatine bones. The third type of mucosa is the *specialized mucosa* covering the anterior two-thirds of the tongue's dorsum: its surface is orthokeratinized and bears the four types of lingual papillae (p. 1724), all of them carrying taste buds except for the filiform papillae. The richly collagenous lamina propria binds the mucosa of the tongue to the underlying muscles.

The surface of the oral mucosa can have various histological characteristics: it may be orthokeratinized, parakeratinized, or non-keratinized, depending upon its location. These designations are based primarily on the appearance of the epithelium in histological sections, a rather crude reflection of more subtle differences detectable with immunohistological and molecular techniques.

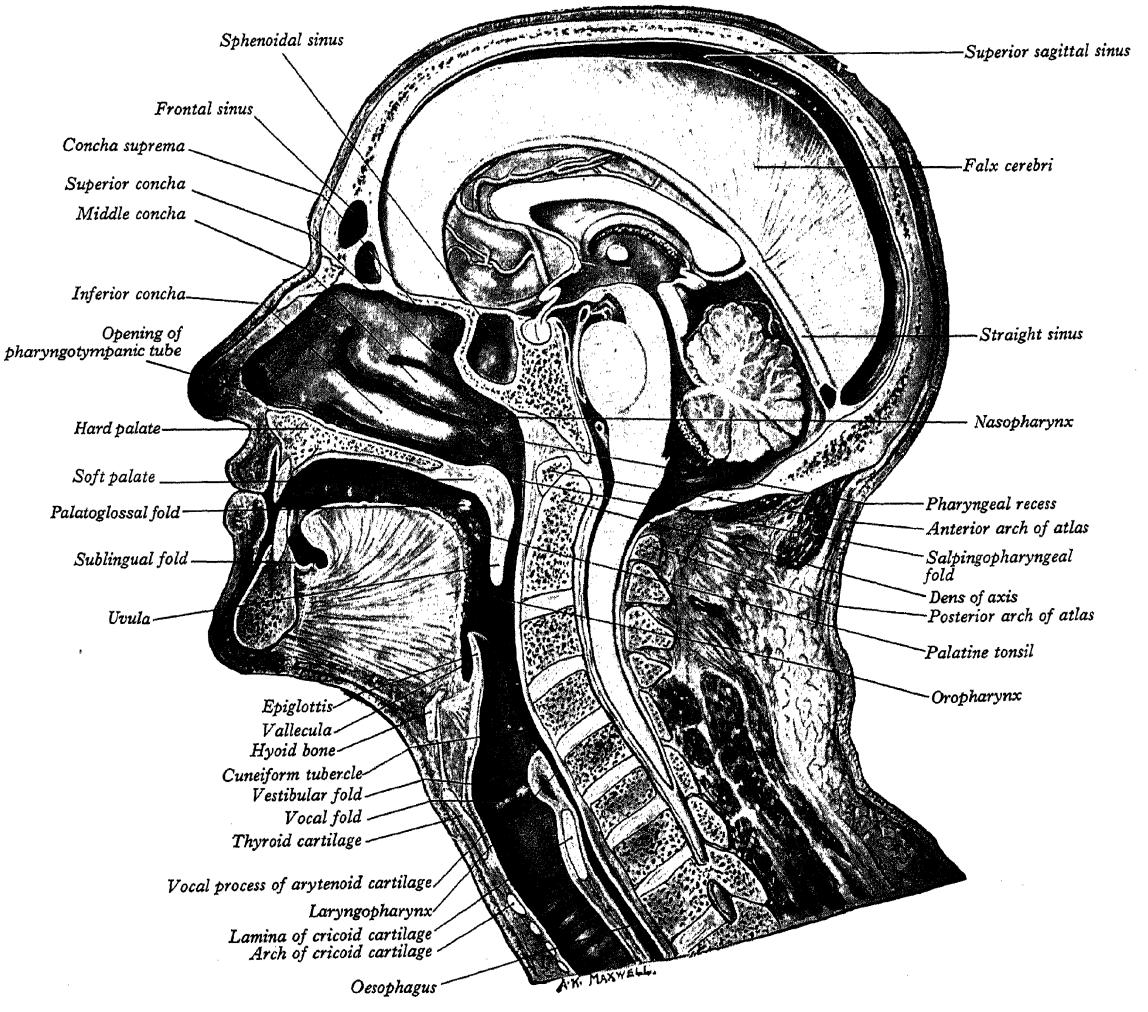
Orthokeratinized epithelium (often referred to as 'keratinized', see p. 71) resembles the epidermis of skin, its most superficial layer consisting of flattened, anucleate epithelial cells which are bright pink in sections stained with haematoxylin and eosin because of the strongly eosinophilic nature of the keratin within them; these superficial squames are sharply demarcated from the underlying granular layer rich in basophilic keratohyalin granules.

Parakeratinized epithelium also has a superficial keratinized layer which is likewise eosinophilic but retains many shrunken nuclei within its flattened cells. Furthermore, the underlying granular layer is usually less distinct than in orthokeratinized epithelium. Occasionally the orthokeratin on the surface of healthy gingivae is replaced by parakeratin. This is assumed to occur when mild inflammation increases the rate of transit of epithelial cells from the basal layer to the surface, thereby compromising their complete differentiation.

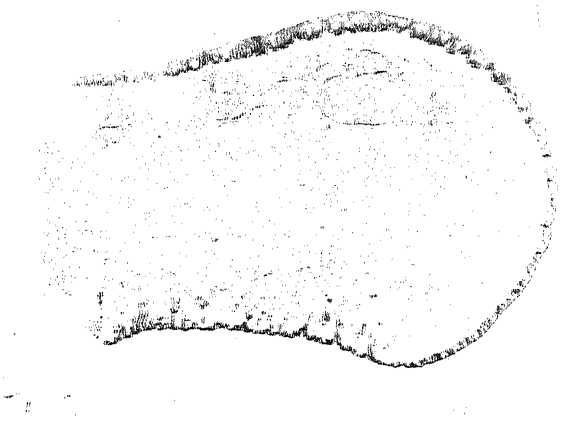
Non-keratinized epithelium lacks an eosinophilic surface layer, and its cells all contain well-defined nuclei. Together with the absence of a subjacent granular layer, this means that there is no clear stratification in the superficial region of non-keratinized epithelium (see also p. 72).

LIPS

The lips are two fleshy folds surrounding the oral orifice (**12.1**). They are lined externally by skin and internally by mucosa, these two layers enclosing the orbicularis oris, labial vessels and nerves, fibro-adipose connective tissue and numerous small labial salivary glands secreting into the vestibule. The skin is continuous with the mucosa



12.1 Median sagittal section through the head and neck. Where it passes through the brain, the section passes slightly to the left of the median plane but, below the base of the skull including the nasal cavity, it passes slightly to the right of the median plane.



12.2 Sagittal section through the lower lip of a neonate, showing thin non-hairy skin of the vermilion border (right) grading into thicker stratified squamous epithelium of the vestibule, with mucosal labial glands (above). Small fasciculi of circumoral muscles are also visible. Haematoxylin and eosin. (Provided by A Hayward; photography: Sarah Smith.)

at the *transitional* or *vermilion border*, a reddish zone (depending upon the degree of melanization) covered by thin keratinized epithelium with connective tissue papillae approaching close to the surface between rete pegs (**12.2**). The colour of this region is due to the proximity of blood vessels to the epithelial surface. The transitional zone is devoid of salivary glands but in the upper lip, and rarely in the lower, it often contains sebaceous glands. The line of contact between the lips (the *oral fissure*) lies just above the cutting edges of the superior incisor teeth; on each side a *labial commissure* forms the *angle of the mouth*, usually near the first premolar tooth. Externally central in the upper lip is a shallow vertical groove, the *philtrum*, ending below in a slight *tubercle* and limited by lateral ridges. Internally each lip is connected to the gum by a *median labial frenulum*, that of the upper lip being the larger. Lateral frenula, of variable number and height, cross the fornix of the vestibule in the region of the canine or premolar teeth. The *labial glands*, situated between the mucosa and orbicularis oris, are about the size of small peas and in structure resemble mucous salivary glands elsewhere (p. 1691).

CHEEKS

The cheeks are continuous in front with the lips, the junction being indicated externally by the *nasolabial sulcus* and lateral to it the *nasolabial fold*, which descends from the side of the nose to each oral angle. Each cheek contains a stratum of skeletal muscle and a variable but usually considerable amount of adipose tissue often encapsulated to form a biconcave mass, the *buccal fat pad* (of Bichat), particularly evident in infants. Also present in the walls of the cheek are fibrous connective tissue, vessels, nerves and numerous small buccal mucous (salivary) glands. The cheek is covered on the inner surface by mucosa, and on the outer surface by skin. The mucosa lining the interior of the cheek is reflected via the vestibule on to the external surfaces of the maxilla and mandible and thence to the gums; it is continuous behind with the palatal mucosa. On the cheek's internal surface, opposite the crown of the second molar, a small papilla bears the opening of the parotid duct which reaches this point by piercing the buccinator muscle. The small *buccal mucous glands* lie mainly between the mucosa and buccinator; four or five of the largest of these glands (*molar glands*) lie external to buccinator around the parotid duct, their ducts piercing buccinator to open near the last molar tooth. Sebaceous glands also occur in the buccal mucosa, often in large numbers, and can be seen as yellowish maculae (*Fordyce spots*), especially if the cheek is stretched; their numbers increase at puberty and during later life (Miles 1958). The principal muscle of the cheek is buccinator, but others are also involved, e.g. zygomaticus major, risorius and platysma (see p. 794).

GUMS (GINGIVAE)

The gums are composed of dense, vascular fibrous tissue, and are normally covered by orthokeratinized stratified squamous epithelium. They are firmly attached to the cement at the necks of the teeth and to the bone of the adjacent alveolar process (**12.4**). The anchoring collagen fibres produce small depressions in the mucosal surface, giving it a stippled appearance. The part of the gum associated with the necks of the teeth (*marginal gingiva*) is not stippled; in young individuals it is partly attached to the enamel via a basal lamina produced by the epithelial cells. The extreme edge of the marginal gingiva is not attached to the enamel but forms the outer lining of a normally shallow gingival crevice around each tooth (see p. 1712). In older individuals the epithelial attachment often migrates on to the cement. The gingival epithelium, like that of the skin, contains melanocytes in its basal layer but these produce melanosomes (and therefore pigmentation) only in the more pigmented races. Langerhans cells, the most peripheral outpost of the immune system (p. 392), occur in the more superficial layers of the mucosal epithelium. The incidence of these last two types of cell has been assessed (Barker 1967).

Nerves of the gums. They come from the maxillary nerve via its greater palatine, nasopalatine and anterior, middle and posterior superior alveolar branches. The mandibular nerve innervates the lower gum by its inferior alveolar, lingual and buccal branches; the buccal branch supplies the external surface of the lower gum as far forward as the mental foramen. The lingual nerve can be palpated where it lies against the alveolar process of the mandible close to its upper margin at the inner aspect of the lower third molar tooth, and here the nerve is at risk during the surgical removal of the tooth.

Vessels in the gums. These usually accompany the nerves. Lymphatics of the upper gum drain to the submandibular nodes; those from the anterior part of the lower gum pass to the submental nodes and from its posterior part to the submandibular nodes.

For a detailed study of the oral cavity, consult DuBrul 1988.

PALATE

The palate, or oral roof, is divisible into two regions: the *hard palate* in front and *soft palate* behind.

Hard palate

The hard palate is formed by the palatine processes of the maxillae and the horizontal plates of the palatine bones (**12.1, 24**). It is bounded in front and at the sides by the superior and inferior arches of the alveolar processes and gums, and is continuous posteriorly with the soft palate. The hard palate is covered by a thick mucosa bound tightly to the underlying periosteum, its more lateral regions also possessing a submucosa containing mucous glands and (anteriorly) adipose tissue. Its covering of stratified squamous epithelium is orthokeratinized, but shows regional variations.

The periphery of the hard palate consists of gingiva, and a zone similarly lacking submucosa runs anteroposteriorly in the midline as a narrow, low ridge, the *palatine raphe*. At the anterior extremity of the raphe an oval prominence, the *incisive papilla*, covers the incisive fossa at the oral opening of the incisive canal (p. 602), also marking the position of the fetal nasopalatine canal (p. 282). Radiating outwards from the palatine raphe in the anterior half of the hard palate are irregular transverse ridges or *rugae*, each containing a core of dense connective tissue. In long-jawed mammals, prominent rugae occur throughout the hard palate and are believed to assist the backwards transport of food during mastication. This function is less important in the human, although the rugae may still have a role in suckling by infants. Their vestigial nature is associated with a considerable variation in form; indeed, each individual may have a virtually unique pattern of rugae, a point of forensic interest.

The submucosa beneath the rugae contains adipose tissue but in the posterior half of the hard palate there are small *mucous palatine salivary glands*. These secrete through numerous small ducts, although bilaterally a larger duct collecting from many of these glands often opens at the paired *palatine foveae*, two sagittally elongated depressions, sometimes a few millimetres deep, which flank the midline raphe at the posterior border of the hard palate. The

upper surface of the hard palate is the floor of the nasal cavity and is covered by ciliated respiratory epithelium.

Soft palate

The soft palate is a mobile flap suspended from the posterior border of the hard palate, sloping down and back between the oral and nasal parts of the pharynx (**12.1**). It is a thick fold of mucosa enclosing an aponeurosis, muscular tissue, vessels, nerves, lymphoid tissue and mucous glands. In its usual position, relaxed and pendant, its anterior (oral) surface is concave, with a median raphe; its posterior aspect is convex and continuous with the nasal floor. Its anterosuperior border is attached to the hard palate's posterior margin, its sides blend with the pharyngeal wall and its inferior border is free, hanging between the mouth and pharynx.

A median conical process, the *uvula*, projects downwards from its posterior border; the palatal arches, two curved folds of mucosa containing muscle, descend laterally from each side of the soft palate (**12.54, 56**). The anterior of these, the *palatoglossal arch*, contains the palatoglossus muscle and descends to the side of the tongue at the junction of its oral and pharyngeal parts, forming the lateral limits of the oropharyngeal isthmus. The posterior *palatopharyngeal arch* contains the palatopharyngeus muscle, and descends on the lateral wall of the oropharynx (p. 1728). The *isthmus of the fauces* is the aperture between the oral cavity and oropharynx guarded on either side by the palatoglossal folds.

Just behind and medial to each upper alveolar process, in the lateral region of the anterior part of the soft palate, a small bony prominence can be felt. This is produced by the pterygoid hamulus, an extension of the medial pterygoid plate (p. 566). The pterygomandibular raphe (p. 816), a tendinous band interposed between buccinator and the superior constrictor muscle, passes downwards and outwards from the hamulus to the posterior end of the mylohyoid line. When the mouth is opened wide, this raphe elevates a fold of mucosa which marks internally the posterior boundary of the cheek.

The oral surface of the soft palate is covered with non-keratinized, stratified squamous epithelium. On its upper nasopharyngeal surface and near the orifices of the auditory tubes it is lined by pseudostratified ciliated ('respiratory') epithelium. Deep to the mucosa on both surfaces are palatine mucous glands; they are most abundant around the uvula and on the oral aspect of the soft palate, where taste buds also occur.

Vessels

The arteries of the palate are the greater palatine branch of the maxillary artery, the ascending palatine branch of the facial artery and the palatine branch of the ascending pharyngeal artery. The veins drain largely to the pterygoid and tonsillar plexuses. The lymph vessels pass to the deep cervical lymph nodes.

Nerves

The *sensory nerves* issue from the greater and lesser palatine, and nasopalatine branches of the maxillary nerve, and also the glossopharyngeal nerve (posteriorly). The lesser palatine nerve also contains taste fibres of facial nerve (greater petrosal) origin supplying taste buds in the oral surface of the soft palate. *Parasympathetic postganglionic secretomotor* fibres arising from the facial nerve via the pterygopalatine ganglion run with these nerves to the palatine mucous glands; it is also possible that some parasympathetic fibres pass to the posterior parts of the soft palate from the glossopharyngeal nerve, perhaps synapsing in the otic ganglion. *Sympathetic fibres* run from the carotid plexus along arterial branches supplying this region.

Palatine aponeurosis

A thin, fibrous *palatine aponeurosis* supports the muscles and strengthens the soft palate; it is attached to the posterior border and inferior surface of the hard palate behind the palatine crest (p. 563). It is thick in the anterior two-thirds of the soft palate but very thin further back. It is composed of the expanded tendons of the tensores veli palatini; near the midline it encloses the musculus uvulae. All the other palatine muscles are attached to it. The anterior third of the soft palate contains little muscle, consisting mainly of the palatine aponeurosis, inferior to which are many mucous glands; this region is less mobile and more horizontal than the rest of the soft palate and is the chief area acted upon by the tensores veli palatini.

Palatine musculature

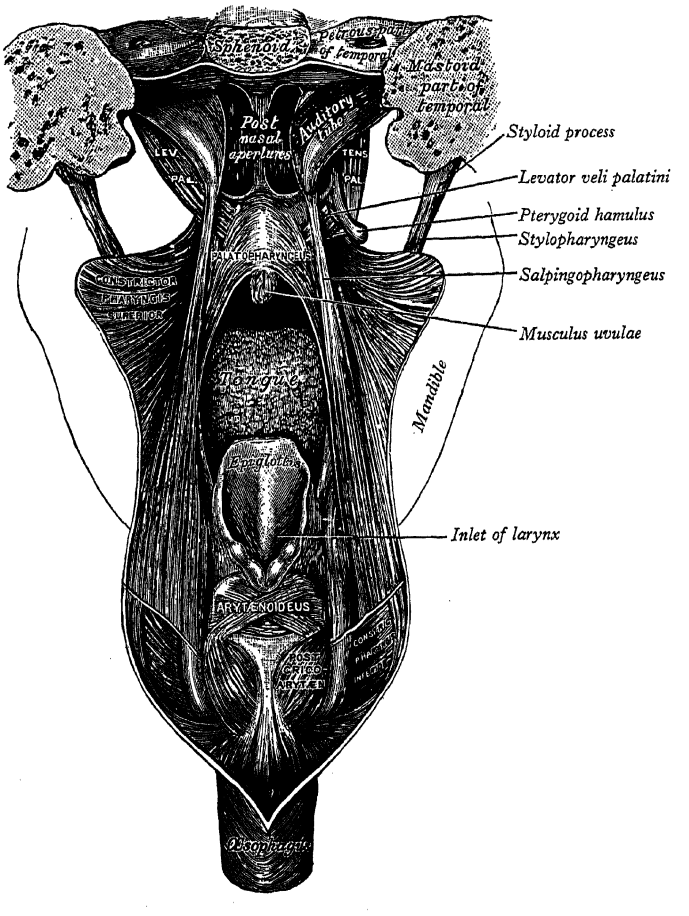
The palatine muscles (**12.3, 61, 67–69**) include levator veli palatini, tensor veli palatini, palatoglossus, palatopharyngeus and musculus uvulae. For their activities in swallowing and speech see page 1732. Their nerve supply is summarized on page 1691.

Levator veli palatini (**12.3, 61, 67–69**). This muscle is cylindrical and lies lateral to the posterior nasal aperture. According to Rohan & Turner (1956) it is attached:

- by a small tendon to a rough area on the inferior surface of the petrous temporal bone in front of the lower opening of the carotid canal
- by muscle fibres to a sheet of fascia descending from the vaginal process of the tympanic bone to form the upper part of the carotid sheath
- by a few fibres to the inferior aspect of the cartilaginous part of the pharyngotympanic tube.

At its origin the muscle is inferior rather than medial to the pharyngotympanic tube and only crosses medial to it at the level of the medial pterygoid plate. Passing medial to the upper margin of the superior constrictor and in front of salpingopharyngeus, its fibres spread in the medial third of the soft palate between the two strands of the palatopharyngeus, its fibres being attached to the upper surface of the palatine aponeurosis as far as the midline where they interlace with those of the contralateral muscle. Thus the two levator muscles form a sling above and just behind the palatine aponeurosis.

Actions. The primary role of the levator veli palatini is to elevate the almost vertical posterior part of the soft palate and pull it slightly backwards. During swallowing, the soft palate is at the same time made rigid by the contraction of the tensores veli palatini and touches the posterior wall of the pharynx, thus separating the



12.3 The muscles of the palate, exposed from the posterior aspect.

nasopharynx from the oropharynx. By additionally pulling on the lateral walls of the nasopharynx posteriorly and medially, the muscles also narrow that space (Honjo et al 1976). The levator veli palatini has little or no effect on the pharyngotympanic tube.

Tensor veli palatini (12.3, 61, 67–69). This is a thin, triangular muscle, lateral to the medial pterygoid plate, pharyngotympanic tube and levator veli palatini. Its lateral surface contacts the upper and anterior part of the medial pterygoid muscle, the mandibular, auriculotemporal and chorda tympani nerves, the otic ganglion and the middle meningeal artery. It is attached to the scaphoid fossa of the pterygoid process and posteriorly to the medial aspect of the spine of the sphenoid; between these two sites it is attached to the anterolateral membranous wall of the pharyngotympanic tube, including its narrow isthmus where the cartilaginous medial two-thirds meets the bony lateral one-third. Some fibres may be continuous with the tensor tympani muscle (Rood & Doyle 1978). Inferiorly, the fibres converge on a delicate tendon which turns medially around the pterygoid hamulus to pass through the attachment of buccinator to the palatine aponeurosis and the osseous surface behind the palatine crest on the horizontal plate of the palatine bone. Between the tendon and the pterygoid hamulus is a small bursa.

Actions. Acting together the tensores tauten the soft palate, principally its anterior part, depressing it by flattening its arch. Alone, the muscle pulls the soft palate to one side. Although contraction of the tensores will slightly depress the anterior part of the soft palate, it is often assumed that the increased rigidity aids palatopharyngeal closure. However, it is now believed that the primary role of the tensor is to open the pharyngotympanic tube, for example during deglutition and yawning, thereby equalizing air pressure with the middle ear and nasopharynx (Maue-Dickson & Dickson 1980).

Musculus uvulae. A bilateral structure, this arises from the posterior nasal spine of the palatine bone and the dorsal surface of the palatine aponeurosis, between the two laminae of which the uvular muscles lie; it runs posteriorly above the levator sling to insert beneath the mucosa of the uvula. A paired structure at its anterior and posterior attachments, for most of its length the two sides are united.

Actions. Elevation and retraction of the uvula; by retracting the uvular mass and thickening the middle third of the soft palate, it aids the levatores in palatopharyngeal closure. Running at right angles to each other, contraction of the levatores and musculi uvuli raises a 'levator eminence' which seals off the nasopharynx 'like a cork in a bottle' (DuBrul 1988).

Palatoglossus (12.67). This is a small fasciculus narrower at its middle than at its ends and forming, with the mucosa overlying it, the palatoglossal arch or fold (12.1, 56, 67). It arises from the oral surface of the palatine aponeurosis about half-way along the soft palate where it is continuous with its fellow and extends forwards, downwards and laterally in front of the palatine tonsil to the side of the tongue; some of its fibres spread over the dorsum of the tongue, others passing deeply into its substance to intermingle with the transversus linguae.

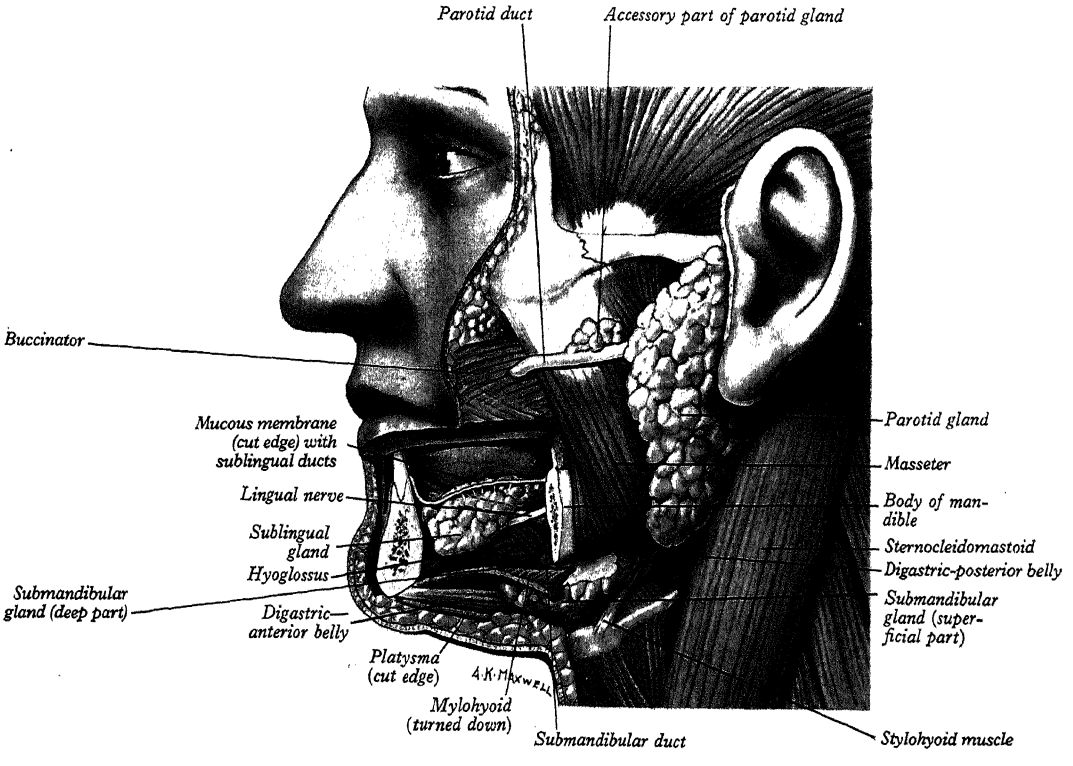
Actions. Palatoglossus elevates the root of the tongue and approximates the palatoglossal arch to its fellow, thus shutting off the oral cavity from the oropharynx.

Palatopharyngeus (12.3, 67). This forms, with its overlying mucosa, the palatopharyngeal arch (12.54). Within the soft palate it is composed of two fasciculi which are attached to the upper surface of the palatine aponeurosis in the same plane but separated from each other by levator veli palatini. The thicker anterior fasciculus is attached to the posterior border of the hard palate as well as to the aponeurosis where some fibres interdigitate across the midline. The posterior fasciculus is in contact with the mucosa of the pharyngeal aspect of the palate; it joins the posterior band of the opposite muscle in the midline. At the soft palate's posterolateral border the two layers unite and are joined by fibres of salpingopharyngeus (p. 1727). Passing laterally and downwards behind the tonsil, palatopharyngeus descends posteromedial to and in close contact with stylopharyngeus, to be attached with it to the posterior border of the thyroid cartilage; some fibres end on the side of the pharynx, attached to pharyngeal fibrous tissue and others cross the midline posteriorly, decussating with those of the opposite muscle. The palatopharyngeus thus forms an incomplete internal longitudinal muscular layer in the wall of the pharynx.

Actions. Together, the palatopharyngei pull the pharynx up, forwards and medially, thus shortening it during swallowing. They also approximate the palatopharyngeal arches and draw them forwards.

Summary of soft palate muscle attachments

In the soft palate the muscles are arranged as follows: the palatine aponeurosis (tendon of the tensores veli palatini) is an intermediate



12.4 Dissection showing the salivary glands of the left side. The cranial region of the superficial part of the submandibular gland has been excised and the cut mylohyoid has been turned down to expose a portion of the deep part of the gland.

sheet, enclosing the uvular muscles near the midline; the levatores veli palatini and the palatopharyngi are attached to its upper surface, the two fasciculi of the latter lying in the same plane, one in front of and the other behind levator veli palatini. The palatoglossi are inserted into the inferior surface of the aponeurosis. (For a description of the palatopharyngeal sphincter, see p. 1730.)

Nerve supply of palatine muscles

Except for tensor veli palatini, which is innervated by the mandibular nerve (p. 1237), all the palatine muscles are supplied by nerve fibres which leave the medulla in the cranial part of the accessory nerve and reach the pharyngeal plexus via the vagus nerve and possibly the glossopharyngeal. More controversially, several investigators have suggested that levator veli palatini is also supplied by the facial nerve. Ibuki et al (1978) report electromyographic evidence that in monkeys this motor route involves the greater petrosal nerve, pterygopalatine ganglion and lesser palatine nerves. In contrast, Keller at al (1984), using retrograde axonal transport in cats, found levator veli palatini motor neurons in the nucleus ambiguus but not in the facial nucleus. These authors also confirmed that tensor veli palatini motor neurons are situated in the trigeminal motor nucleus.

Defects of the palate

The condition of congenital cleft palate has been noted already as a developmental defect (p. 284). Rarely, palatopharyngeal incompetence may be due to muscle hypoplasia, particularly of the musculus uvulae; submucous clefts resulting from this may be revealed clinically as a V-shaped notch in the midline of the soft palate during function. Paralysis of the soft palate may follow diphtheria due to the action of the toxin on the nerve cells of the medulla oblongata; in this state, the voice becomes nasal and fluids regurgitate into the nose during swallowing; the palate is visibly flaccid and motionless and also anaesthetic. Other pathological processes involving the glossopharyngeal, vagus and accessory nerves or their nuclei in the medulla oblongata also cause palatal paralysis.

SALIVARY GLANDS

A salivary gland is any cell or organ discharging a secretion into the oral cavity. Distinction is customarily made between the *major salivary glands*, located at some distance from the oral mucosa, with which they connect by extraglandular ducts, and the *minor salivary glands* which lie in the mucosa or submucosa, opening directly through the mucosa or indirectly via many short ducts. In humans the major salivary glands comprise the paired parotid, submandibular and sublingual glands; the minor salivary group includes those in the tongue, the anterior lingual glands and numerous small lingual (including von Ebner's) glands of the lingual mucosa (see p. 1724). Elsewhere in the oral cavity are the small labial, buccal and palatal glands (p. 1688). Their functions include: lubrication of food to assist deglutition, moistening the buccal mucosa (important for speech), provision of an aqueous solvent necessary for taste and as a fluid seal for sucking and suckling, secretion of digestive enzymes such as salivary amylase and of hormones and other compounds, such as a glucagon-like protein (Lawrence et al 1977) and possibly serotonin (Feyrter 1961), and secretion of antimicrobial agents (including IgA, lysozyme and lactoferrin). An illustration of the position of the major salivary glands and their ducts is shown in **12.4**.

PAROTID GLANDS

The paired parotid glands (**12.4–8**) are the largest of the salivary glands; each has an average weight of about 25 g and is an irregular, lobulated, yellowish mass, lying largely below the external acoustic meatus between the mandible and sternocleidomastoid. The gland also projects forwards on the surface of the masseter, where a small, usually detached part lies between the zygomatic arch above and the parotid duct below, the *pars accessoria* or *socia parotidis*. The parotid consists almost entirely of serous glandular tissue (see p. 74).

The *capsule* of the gland is derived from the deep cervical fascia; its superficial layer is dense, closely adherent and sends fibrous septa into the gland, it is attached to the zygomatic arch. Medial to the gland it is firmly attached to the styloid process, mandible and tympanic plate, blending with the fibrous sheaths of related muscles. The fascia extending from the styloid process to the mandibular angle forms the stylomandibular ligament, which intervenes between the parotid and submandibular glands. The parotid gland is like an inverted, flat, three-sided pyramid, presenting a small superior surface, and superficial, anteromedial and posteromedial surfaces; it tapers inferiorly to a blunt apex.

The concave *superior surface* is related to the cartilaginous part of the external acoustic meatus and posterior aspect of the temporomandibular joint; here the auriculotemporal nerve curves round the neck of the mandible, embedded in the gland's capsule. The *apex* overlaps the posterior belly of the digastric and the carotid triangle to a variable extent.

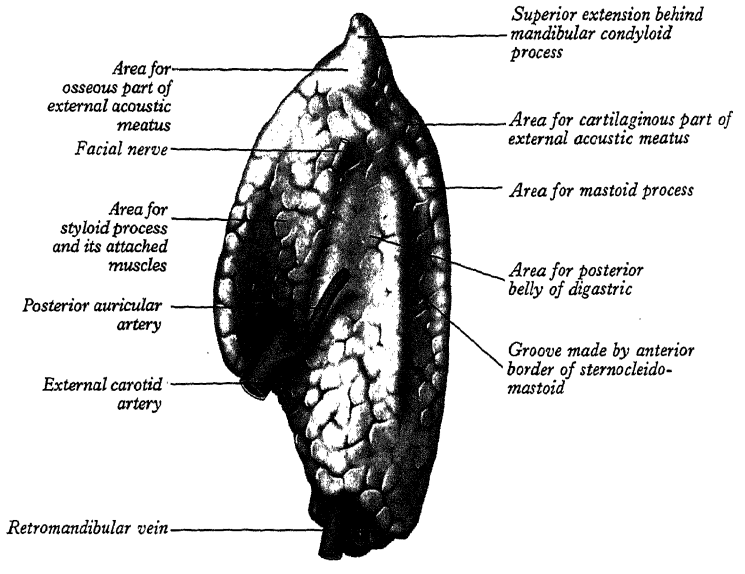
The *superficial surface* is covered by skin and superficial fascia, which contains the facial branches of the great auricular nerve, superficial parotid lymph nodes and the posterior border of platysma. It extends upwards to the zygomatic arch, back to overlap the sternocleidomastoid, down to its apex postero-inferior to the mandibular angle and forwards superficial to the masseter below the parotid duct (**12.4, 7**).

The *anteromedial surface* is grooved by the posterior border of the mandibular ramus. It covers the postero-inferior part of the masseter, the lateral aspect of the temporomandibular joint and the adjoining part of the mandibular ramus, passing forwards medial to the ramus to reach the medial pterygoid. Branches of the facial nerve emerge on the face from the anterior margin of this surface.

The *posteromedial surface* is moulded to the mastoid process, sternocleidomastoid, posterior belly of the digastric and the styloid process and its muscles. The external carotid artery grooves this surface before entering the gland. The internal carotid artery and internal jugular vein are separated from the gland by the styloid process and its muscles (**12.7**). The anteromedial and posteromedial surfaces meet at a medial margin which may project so deeply as to be in contact with the lateral wall of the pharynx.

Several structures traverse the gland partly or wholly and even branch within it. The external carotid artery enters the posteromedial surface, dividing into the maxillary artery, which emerges from the anteromedial surface, and the superficial temporal artery which gives off its transverse facial branch in the gland and ascends to leave its upper limit (**12.6, 7**). The posterior auricular artery may also branch from the external carotid within the gland, leaving by its posteromedial surface. The retromandibular vein (p. 1578), formed by the union of the maxillary and superficial temporal veins (which enter near the points of exit of the corresponding arteries), is superficial to the external carotid artery and emerges behind the gland's apex to join the posterior auricular vein, forming the external jugular; it has a communicating branch which leaves anterior to the apex to join the facial vein. Most superficial is the facial nerve, entering high on the posteromedial surface (**12.7**) and passing forwards and down behind the mandibular ramus in two main divisions, from which its terminal branches diverge to leave by the anteromedial surface, passing medial to its anterior margin.

The parotid gland develops as an outgrowth from the buccal cavity (p. 175), spreading back towards the ear and covering the facial nerve; prolongations of the gland penetrate medially between the branches of the nerve to form its deeper part, the largest part being between the nerve's main temporal and cervical divisions (Bailey 1947, McKenzie 1948). These processes finally engulf the nerve and its branches, which are sometimes considered to divide the gland into a superficial and a deep lobe.



12.5 The right parotid gland: posteromedial aspect.

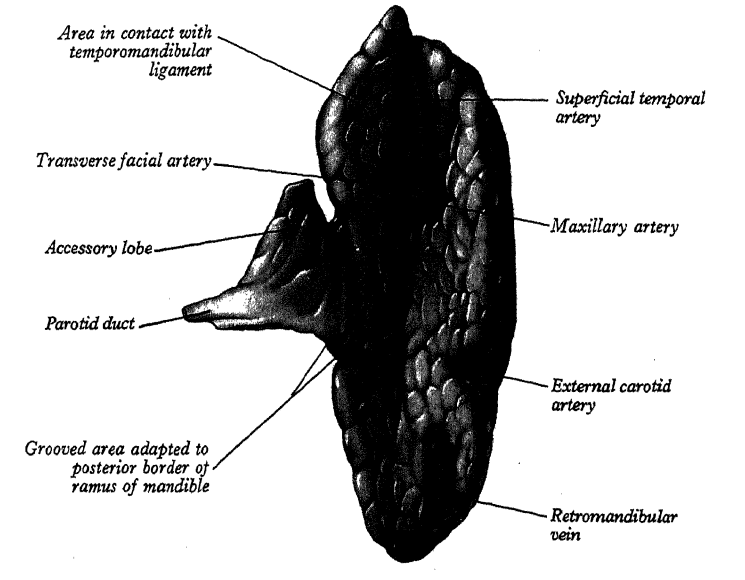
Parotid duct (12.4, 16A).

About 5 cm long, this begins by the confluence of two main tributaries within the anterior part of the gland (p. 1699), then crosses the masseter and at its anterior border turns medially at almost a right angle, traversing the corpus adiposum (suctorial pad of infants) and the buccinator. It then runs obliquely forwards for a short distance between the buccinator and the oral mucosa to open upon a small papilla opposite the second upper molar crown. While crossing the masseter it receives the accessory parotid duct and here lies between the upper and lower buccal branches of the facial nerve; the accessory part of the gland and the transverse facial artery are above it. The buccal branch of the mandibular nerve, emerging from beneath the temporalis and masseter, is just below the duct at the masseter's anterior border.

The wall of the parotid duct is thick, with an external fibrous layer containing smooth muscle and a mucosa lined by low columnar epithelium (see below). Its calibre is about 3 mm, although smaller at its oral orifice.

Surface anatomy

The parotid duct can be felt on the face or more easily in the vestibule of the mouth, and rolled on the anterior border of the masseter, by pressing the finger **backwards** on it (with teeth clenched to make the muscle tense). The anterior border of the parotid gland is represented by a line descending from the mandibular condyle to a point just above the middle of the masseter and then to a point about 2 cm below and behind the mandibular angle. Its concave upper border corresponds to a curve traced from the mandibular condyle across the ear's lobule to the mastoid process. The posterior border is indicated by a straight line drawn between the posterior ends of the anterior and upper borders. The parotid duct corresponds to the middle third of a line drawn from the lower border of the tragus to a point midway between the nasal ala and upper labial margin.



1692 12.6 The right parotid gland: anteromedial aspect.

Vessels and nerves

The parotid **arterial supply** is from the external carotid and its branches within and near the gland. The **veins** drain to the external jugular, through local tributaries. The **lymph vessels** end in the superficial and deep cervical lymph nodes, interrupted by two or three nodes lying on and within the gland. The **efferent innervation** is autonomic, consisting of sympathetic fibres from the external carotid plexus and parasympathetic fibres which reach it via the tympanic branch of the glossopharyngeal nerve relaying in the otic ganglion and then travelling along the auriculotemporal nerve. Clinical observations suggest that in humans the gland also receives secretomotor fibres through the chorda tympani (Reichert & Poth 1933, Diamant & Wiberg 1965). Holmberg (1972) has shown that in **dogs** secretomotor fibres pass to the parotid gland from the maxillary plexus and the facial and auriculotemporal nerves, a supply unconfirmed in man. The termination of these supplies is still controversial. Studies in **cats** suggest that both parasympathetic and sympathetic fibres end in relation to glandular cells (Génis-Gálvez et al 1966, and see below).

SUBMANDIBULAR GLANDS

The paired submandibular glands (**10.81**, **12.4**, 7) are irregular in shape and about the size of walnuts. Each consists of a large superficial and a smaller deep part, continuous with each other around the posterior border of the mylohyoid. They are seromucous (but predominantly serous) glands.

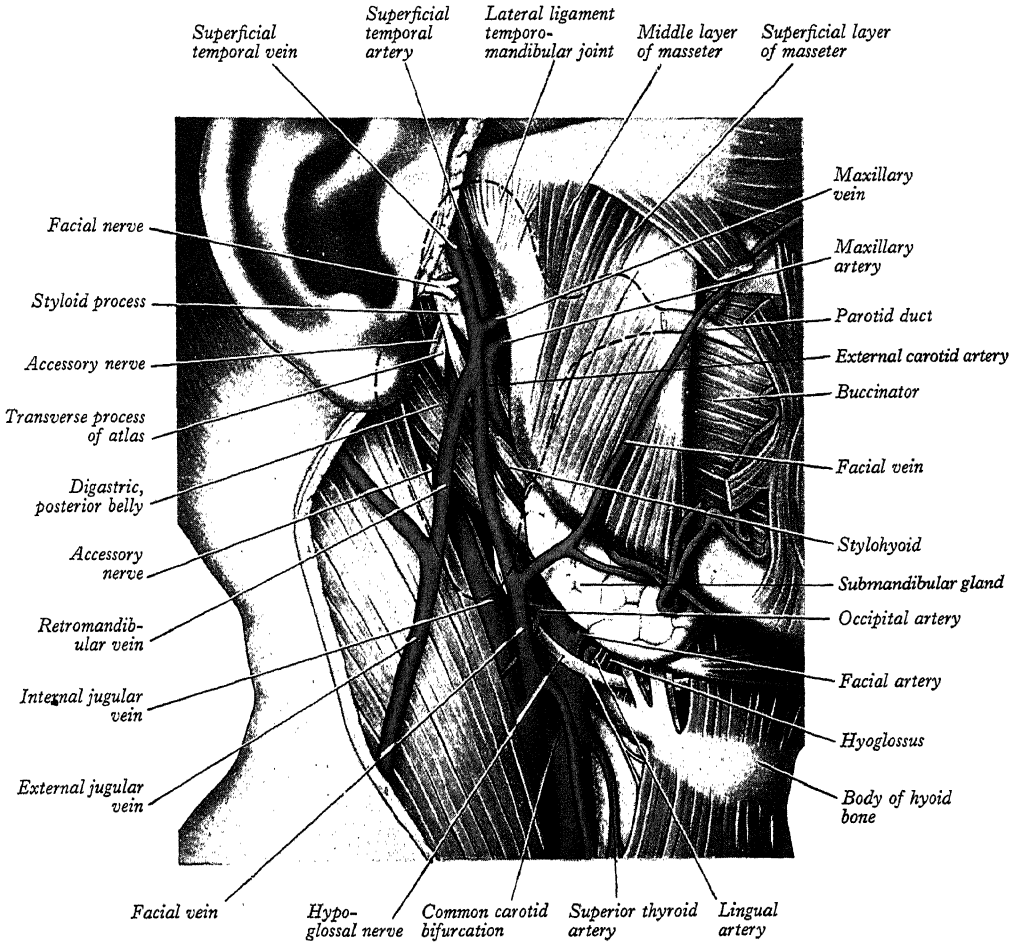
The *superficial part*, situated in the digastric triangle, reaches forward to the anterior belly of the digastric and back to the stylomandibular ligament, which separates it from the parotid gland. Above, it extends medial to the mandible's body; below, it usually overlaps the intermediate tendon of the digastric muscle and the hyoidean attachment of stylohyoid. It has an inferior, a lateral and a medial surface and is partially enclosed between two layers of deep cervical fascia extending from the hyoid's greater cornu; one layer passes to the mandible's lower border, covering the gland's inferior surface, the other passes to the mylohyoid line on the medial surface of the mandible and covers the gland's medial surface.

The *inferior surface*, covered by skin, platysma and deep fascia, is crossed by the facial vein and the facial nerve's cervical branch; near the mandible the submandibular lymph nodes are in contact with the gland and some may be embedded in it (p. 1612).

The *lateral surface* is in relation with the submandibular fossa (on the medial surface of the mandibular body) and the mandibular attachment of the medial pterygoid; the facial artery grooves its posterosuperior part, lying at first deep to the gland and then emerging between its lateral surface and the mandibular attachment of the medial pterygoid to reach the mandible's lower border.

The *medial surface* is related anteriorly to mylohyoid, separated from it by the mylohyoid nerve and vessels and branches of the submental vessels. More posteriorly, it is related to styloglossus, the stylohyoid ligament and the glossopharyngeal nerve, which separate it from the pharynx; in its intermediate part the medial surface is related to hyoglossus, separated from it by styloglossus, the lingual nerve, submandibular ganglion, hypoglossal nerve and deep lingual vein (sequentially from above down). Below, the medial surface is related to stylohyoid and the posterior belly of digastric.

The *deep part* of the gland extends forwards to the posterior end of the sublingual gland and lies between mylohyoid inferolaterally and hyoglossus and styloglossus medially; above it runs the lingual nerve and, below it, the hypoglossal nerve and deep lingual vein.



12.7 Drawing of a dissection to show the principal immediate deep relations of the parotid gland. The outline of the parotid gland is indicated by the interrupted black line.

The gland is palpable between an index finger placed on the floor of the mouth and a thumb placed below the floor, anteromedial to the angle of the mandible.

Submandibular duct (12.16B, 60).

About 5 cm long, this has a thinner wall than the parotid duct. It begins from numerous tributaries in the superficial part of the gland and emerges from the medial surface of this part of the gland behind the posterior border of mylohyoid; it traverses the deep part, passing at first up and slightly back for 4 or 5 mm and then forwards between mylohyoid and hyoglossus. Passing between the sublingual gland and genioglossus it opens in the floor of the mouth on the summit of the sublingual papilla at the side of the frenulum of the tongue (**12.55**). On hyoglossus it lies between the lingual and hypoglossal nerves, but at the muscle's anterior border it is crossed laterally by the lingual nerve, terminal branches of which ascend on its medial side (**12.60**). As it traverses the gland's deep part it receives small tributaries draining this part of the gland. Salivary calculi occasionally occur in the submandibular duct; they are radio-opaque and may be palpable.

Vessels and nerves

The arteries supplying the submandibular gland are branches of the facial and lingual anteries; the veins correspond. The lymph vessels drain into the deep cervical group of lymph nodes, particularly the jugulo-omohyoid node, interrupted by the submandibular nodes, some of which are in close relation with the anterior end and medial aspect of the superficial part of the gland and may be embedded in it. The nerves are derived from the submandibular ganglion, through which it receives fibres from the chorda tympani (parasympathetic), the lingual branch of the mandibular nerve (sensory) and the sympathetic trunk. In dogs and cats the gland receives its nerve supply through the subsidiary ganglion of Langley (p. 1297), but in humans the parasympathetic nerve supply (chorda tympani) relays mainly in the submandibular ganglion. Small parasympathetic ganglia may occur in the gland's hilum and in the branches of the submandibular ganglion passing to it. Garrett and Kemplay (1977), using catecholamine fluorescence and electron micrography, observed that in cats all adrenergic fibres are derived from the superior cervical sympathetic ganglion.

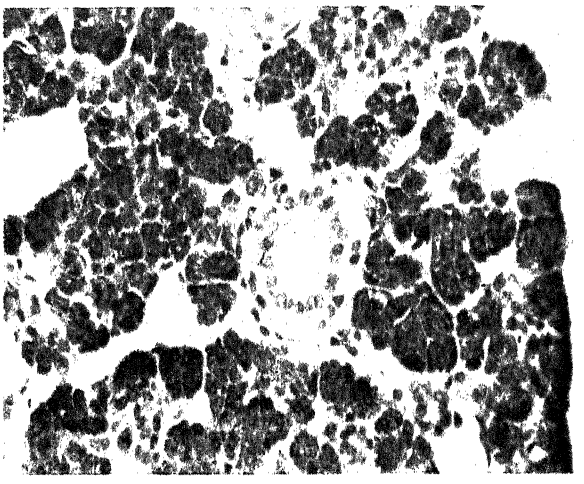
SUBLINGUAL GLANDS

The paired sublingual glands (**12.4**), the smallest of the main salivary glands, lie beneath the oral mucosa, each in contact with the sublingual fossa on the lingual aspect of the mandible, close to the symphysis. Each is narrow, flat, shaped like an almond, and weighs 3–4 g. The sublingual glands are mucous in type (p. 74).

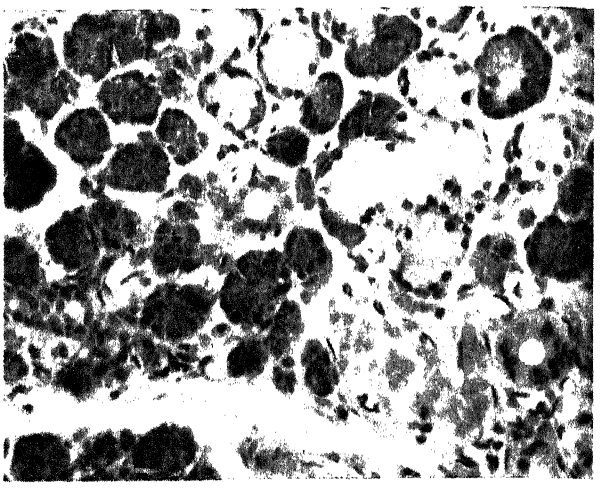
Above the gland is the mucosa of the oral floor, raised as a sublingual fold; **below** is mylohyoid; **in front** is the anterior end of its fellow; **behind** lies the deep part of the submandibular gland; **lateral** is the mandible above the anterior part of the mylohyoid line, and **medial** is genioglossus, separated from it by the lingual nerve and submandibular duct. It has 8–20 excretory ducts; of the *smaller sublingual ducts* most open separately on the summit of the sublingual fold and a few sometimes into the submandibular duct. From the anterior part of the gland small rami sometimes form a *major sublingual duct*, opening with or near to the orifice of the submandibular duct.

Vessels and nerves

The arterial supply is from the sublingual and submental arteries. The veins correspond to the arteries. Innervation is by the lingual



12.8 Section through the parotid gland, stained with haematoxylin and eosin. Magnification x 350.



12.9 Section of the submandibular gland, stained with haematoxylin and eosin. Magnification x 350.

nerve, chorda tympani and sympathetic fibres. The parasympathetic relay is in the submandibular ganglion; neurons may occur among its distal fibres to the lingual nerve forming a distinct sublingual ganglion. The precise terminations of the nerve supply are not fully known (see below).

MICROSTRUCTURE OF MAJOR SALIVARY GLANDS

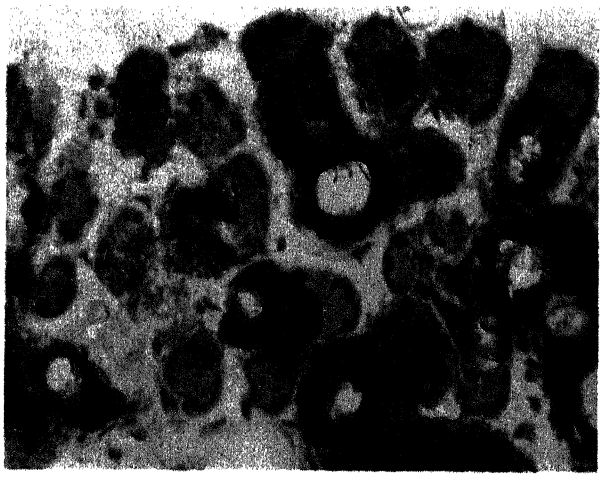
These glands are compound racemose in type (12.9–13) and have numerous lobes composed of lobules linked by dense connective tissue containing excretory (collecting) ducts, blood vessels, lymph vessels, nerve fibres and small ganglia. Each lobule has a single duct, whose branches begin as dilated secretory 'endpieces' or acini. Their primary secretion is modified as it traverses intercalated, striated and excretory ducts into one or more main ducts which discharge saliva into the oral cavity (see below).

Salivary acini or 'endpieces' (12.13)

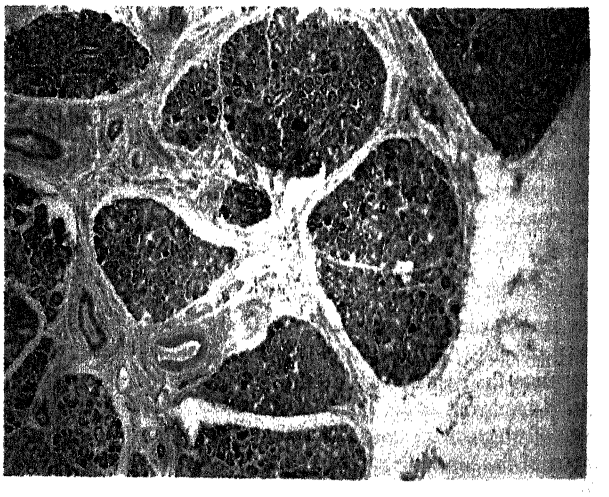
The variety of different terms used to describe the form and cytology of secretory acini or endpieces has caused much confusion. Garrett (1976) and Young and van Lennep (1978) have appraised the problems involved. (The official term is *portio terminalis*—of acinar, alveolar or tubulo-alveolar types—inelegantly translated as 'endpiece'.)

In the following description a secretory 'endpiece' is termed an *acinus* if approximately spheroidal, a *tubule* if elongate; *tubuloacini* are intermediate in shape. The secretory cells of acini are pyramidal, with narrow luminal apices and broad bases; those of tubules are more cylindrical. Such cells, the main producers of salivary protein and glycoprotein, are usually described according to their appearance as *serous, seromucuous* or *mucous*, though unfortunately without unanimity in use. A serous secretion of low viscosity, and a highly viscous mucus were correlated initially with serous and mucous cells distinguished by simple histological staining methods. Improved techniques later identified a range for seromucous secretions. It is now established that the products of these cells form an almost continuous series, from serous secretions with negligible amounts of acidic proteoglycans to mucous secretions rich in them. Applying the criteria of Young and van Lennep (1978) glandular cells are here dubbed: *serous* if the granules are small, discrete, homogeneous, generally eosinophilic and electron-dense; *mucous* if their granules are larger, close-packed and ill-defined, with low eosinophilia and a homogeneous, fairly electron-translucent matrix; or *seromucous* if they are intermediate in appearance, with granules either close-packed, eosinophilic and homogeneous, or more discrete, larger and heterogeneous. A gland or secretory acinus with only one type of cell is described as *homocrine*, while one containing more than one type is *heterocrine*.

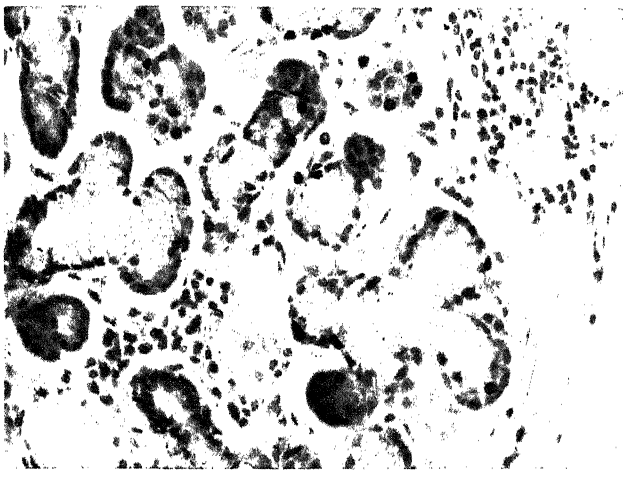
The secretory 'endpieces' of the human **parotid gland** are mainly seromucous (or serous) acini (12.8); mucous acini are rare. In the



12.10 Section through the submandibular gland, stained with haematoxylin and alcian blue. Mucous cells are stained blue, the serous glands only with haematoxylin and eosin. Magnification x 350.



12.11 Section through the sublingual gland, stained with haematoxylin and eosin. Magnification x 80.



12.12 Section through the sublingual gland, stained with haematoxylin and eosin. Magnification × 350.

submandibular gland acini are usually seromucous, with some mucous ones. (**12.9**, 10) In the **sublingual gland** (**12.11**, 12) they are typically mucous tubules, but seromucous cells also occur, frequently as acini or as *demilunes* (Young & van Lennep 1978). Seromucous demilunes, which also exist in submandibular glands of many mammalian species, are crescentic groups of glandular cells found at the bases of some mucous endpieces (**12.13**); sited between the mucous cells and basal lamina, they apparently communicate with the lumen by fine canaliculi which pass between the mucous cells. Using the criteria described above all the major human salivary glands are thus heterocrine.

The ultrastructure of these glandular cells is shown diagrammatically in **12.13**. *Seromucous* (and *serous*) *cells* are roughly pyramidal. The basal plasmalemma is usually smooth, while the lateral is plicated and interdigitates with that of the adjacent cells. The apical (luminal) surface bears microvilli, between which are often endocytic vesicles. Discrete, secretory canaliculi lie between the cells; limited basilaterally by junctional complexes, they open into the lumen of the 'endpiece'; their zonulae occludentes are often assumed to form a continuous seal around each cell but freeze-fracture micrographs of parotid 'endpiece' tight junctions in rats (de Camilli et al 1976) suggest that the 'seals' may be incomplete. Nuclei vary in shape and position, but are more spheroidal and less basal than in mucous cells. Apically the cytoplasm is filled by secretory granules of variable form (Tandler 1972; Riva & Testa-Riva 1973); a conspicuous feature of the infranuclear cytoplasm is an abundant granular endoplasmic reticulum arranged in stacks of parallel, flat cisternae. Golgi complexes are supranuclear with adjacent small coated and smooth vesicles. Elongated mitochondria, lysosomes, microfilaments and occasional large lipid droplets also occur.

Mucous cells are cylindrical; their luminal plasma membrane is smoother and secretory canaliculi between the cells are rare. The supranuclear cytoplasm is typically packed with large, electron-translucent, frequently fused secretory droplets. Granular endoplasmic reticulum and Golgi complexes resemble those of serous and seromucous cells, but the nucleus is flatter and more basal.

Ducts of salivary glands (12.13)

Leading consecutively from the secretory 'endpieces' are *intercalated, striated* and *excretory ducts*.

In *intercalated ducts*, the lining cells are cuboidal or flat. Their cytoplasm contains long mitochondria, a few cisternae of granular endoplasmic reticulum, juxtanuclear Golgi complexes, lysosomes and secretory granules. While this suggests little participation in protein synthesis, it does not preclude involvement in the addition of water and electrolytes to saliva; the cells responsible for this, in either 'endpiece' or duct, are unknown but, although this function is often assigned to glandular cells, the intercalated ducts may also be involved.

In *striated ducts* (**12.13**) the lining cells are basally striated, 'like a thick lawn' according to Pfluger (1866). Ultrastructurally, these striations are seen to be regions of highly folded basal plasmalemma, between which are columns of packed mitochondria. These folds are also interdigitated laterally with those of adjacent cells, often linked by desmosomes. This folding and local abundance of mitochondria is typical of many epithelial cells engaged in electrolyte transport, as these cells certainly are; they transport potassium into saliva and by reabsorbing sodium ions in excess of water they render saliva hypotonic (Thaysen et al 1954). The lateral plasmalemmae of cells lining striated ducts are linked by 'leaky' junctional complexes (Garrett & Parsons 1974). The luminal plasmalemma bears microvilli and their cytoplasm often extends into the lumen as apical blebs which may be shed into the saliva (apocrine secretion: p. 74; see also Takano 1969, Garrett 1976). As well as modifying electrolyte composition, striated ducts secrete immunoglobulin A (Kraus & Mestecky 1971), lysozyme (Kraus & Mestecky 1971) and kallikrein (Garrett & Kidd 1975). Immunoglobulin A is produced by subepithelial plasma cells.

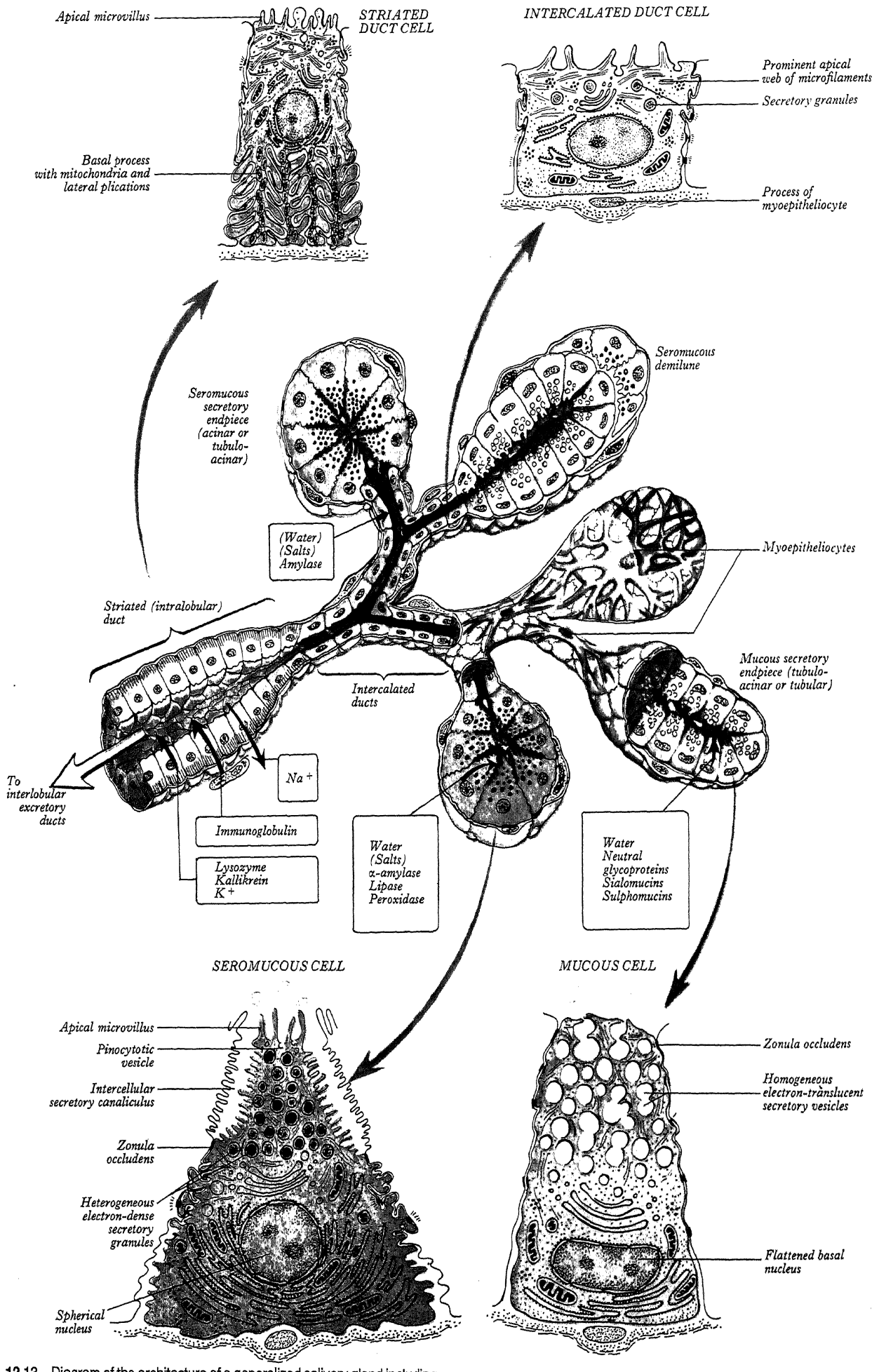
For excretory ducts few ultrastructural details have been recorded; in rats they are lined by simple columnar or pseudostratified epithelium, mainly of tall columnar cells with basal striations containing packed, elongate mitochondria (Tamarin & Sreebny 1965). These striations, and their more intimate relation to capillaries than elsewhere in the ductual system, suggest that excretory ducts are more than passive conduits; an involvement in electrolyte transport is possible (Young & van Lennep 1978).

Myoepitheliocytes of salivary glands (12.13–15)

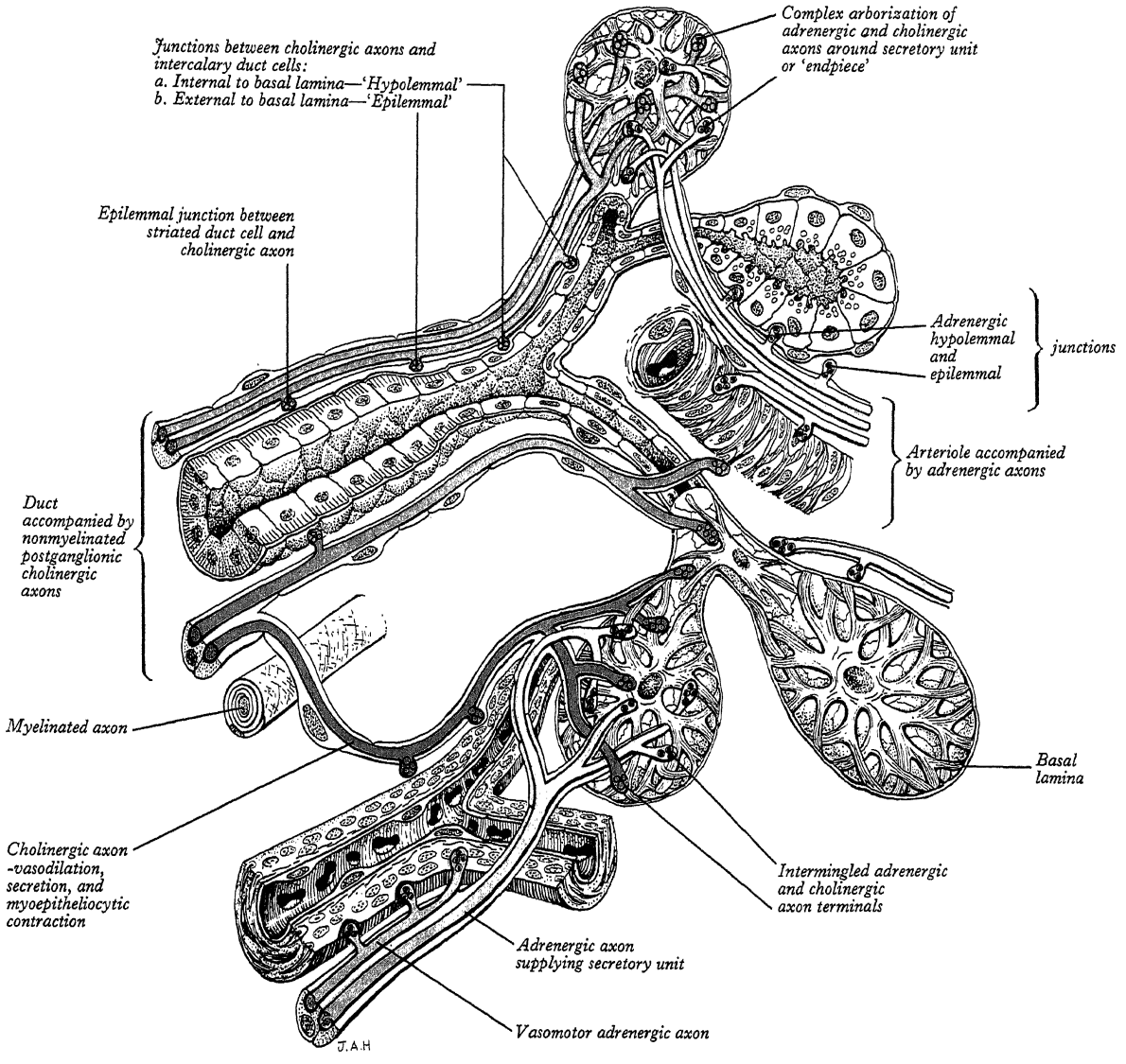
These contractile cells are associated with intercalated ducts and secretory endpieces, lying between the basal lamina and the epithelial cells proper, and also with intra- and extralobular ducts (Chaudhry et al 1987). Garrett and Emmelin (1979) summarized the effects of myoepithelial contraction as follows: the outflow of saliva is accelerated, luminal volume of intercalated ducts and endpieces is reduced, secretory pressure is aided, the underlying parenchyma supported, salivary flow is helped to overcome peripheral resistance and, in certain circumstances, discharge from the actual secretory cells is also assisted.

The shape of salivary myoepitheliocytes depends on their location: in endpieces they are stellate, dendritic, with long overlapping processes ('basket cells') which, with those of other such cells, form a reticulum around each endpiece. Those in the walls of ducts are fusiform, with fewer branches, and extend along the intercalated ducts longitudinally. 'Endpiece' myoepitheliocytes have a central perikaryon with four to eight radial processes, each with two or more successions of branches which cross but do not fuse or extend on to the ducts. In contrast, myoepitheliocytic processes in intercalated ducts seldom branch and often overlap with those of the endpieces.

Myoepitheliocytic cytoplasm (**12.15**) may be divided into filamentous and non-filamentous compartments, the latter containing the nucleus, juxtanuclear Golgi complexes, lysosomal bodies and mitochondria. Globules of neutral fat may occur in human cells (Garrett 1963). The filaments, conspicuous in the processes and their rami resemble the myofilaments of smooth muscle cells (p. 738). Both thin (4 nm) and thick (10 nm) filaments are described, the former arranged longitudinally in processes, with the less numerous thick filaments scattered amongst them. Filaments often pass to attachment plaques on the basal plasmalemma, causing indentations. Basal lamina opposite the plaques appears thicker and may be linked to the cells at these sites. Bannerjee et al (1977) have shown that the basal lamina strengthens and supports the adjacent epithelium. When myoepitheliocytes contract, the basal lamina is probably tensed at the attachment plaques (Garrett & Emmelin 1979). Numerous caveolae are commonly associated with the stromal plasmalemma, but less frequently so with the plasmalemma adjacent to the epithelial cells. Myoepitheliocytes are linked to secretory and ductual cells by desmosomes and occasional cilia extend from them into indentations of the adjacent epithelial cells. Cilia were first observed by Tandler (1965) in myoepitheliocytes of human submandibular glands and subsequently described in other human salivary glands (Tandler et al 1970) and in glands of other species (Cutler & Chaudhry 1973). Garrett and Emmelin (1979) suggest that there may be a cilium on each salivary myoepitheliocyte, as proposed by Stirling and Chandler



12.13 Diagram of the architecture of a generalized salivary gland including ultrastructural details. Solid and outlined black arrows indicate direction of saliva transport.



12.14 The innervation of the ducts, secretory units and arterioles in a generalized salivary gland.

(1976) for human mammary myoepitheliocytes (p. 423). The cilia may have a chemoreceptive and/or mechanoreceptive role.

Salivary myoepitheliocytes appear to have both sympathetic and parasympathetic innervation (Garrett 1972, 1976), with several axons of either type, or jointly, supplying a single cell. In the sublingual gland of the rat, myoepitheliocytes may have only cholinergic innervation (Templeton & Thulin 1978). Stimulation by sympathetic or by parasympathetic nerves may result in myoepitheliocyte contraction (Garrett & Emmelin 1979). For further details of these cells, see p. 71.

CONTROL OF SALIVARY GLAND ACTIVITY

The observed wide and rapid variation in the composition, quantity and rate of salivary secretion in response to various stimuli suggests an elaborate control mechanism (Emmelin 1972). In some glands salivary secretion is spontaneous; in others secretion follows different types of sensory stimulation: gustatory, nociceptive, olfactory and tactile. Secretion may be continuous, but at a low resting level, and may be in part spontaneous, although it is mainly a response to the drying of the oral and pharyngeal mucosae. A rapid increase can be superimposed on the resting level, e.g. during mastication or when stimulated by the autonomic innervation. The controlled variation in the activity of the many types of salivary effector cells (serous, as well as seromucous and mucous secretory cells, myoepitheliocytes, epithelial cells of all the ductual elements and the smooth muscle of local blood vessels) affects the quantity and quality of saliva. The control of these is both hormonal and neural.

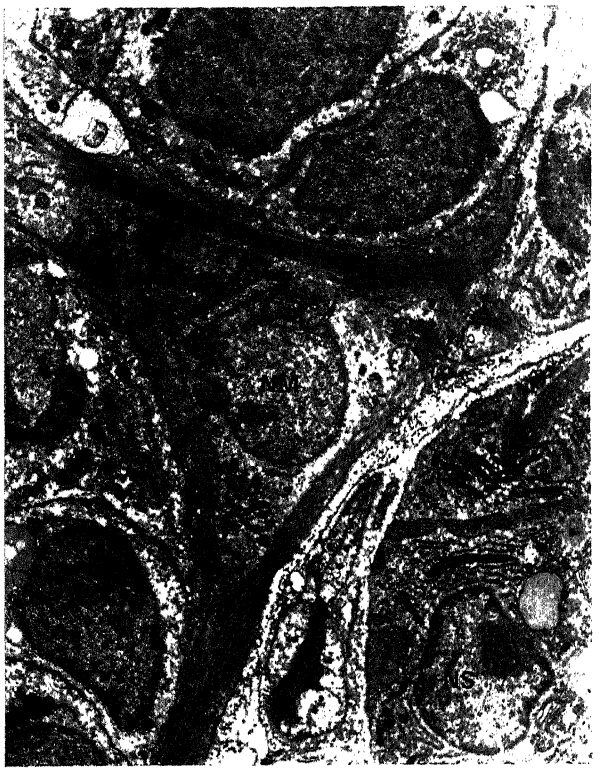
Hormonal control

The effects of circulating hormones upon salivary secretion were reviewed by Blair-West et al (1967). There is no clear evidence that they evoke secretion directly at physiological levels, but they may alter the response of glandular cells to neural stimuli. Local hormones, however, have profound effects in feline submandibular glands; e.g. vasodilatation, though neurally initiated, is maintained by plasma-kinins formed locally when kallikrein is released from secretory cells stimulated by sympathetic amines (Gautvik et al 1972).

Neural control

Most salivary glands, except those secreting spontaneously, depend on autonomic nerves to evoke secretion, and in all of them salivary flow is mainly under nervous control. The nerves involved are cholinergic (parasympathetic) and adrenergic (sympathetic) (Garrett 1976).

The typical pattern of innervation is shown in **12.14**, but details vary in different glands and species (Garrett 1972); differences may also occur with age (Yohro 1971). Only the more constant features are illustrated and described here. Cholinergic nerves often accompany ducts and arborize freely around secretory endpieces,



12.15 Transmission electron micrograph of a myoepitheliocyte of a salivary gland. The superficial filamentous and juxtanuclear non-filamentous compartments of the cytoplasm can be seen. NM = nucleus of myoepitheliocyte; NS = nucleus of secretory cell. (Provided by R M Palmer, UMDS, Guy's Campus, London.)

but adrenergic nerves usually enter glands along arteries and ramify with them. The main secretomotor nerves contain largely non-myelinated axons, but a few myelinated axons occur, presumably either preganglionic efferent or afferent. Postganglionic efferent axons, like those elsewhere (Norberg 1967), show periodic dilatations containing mitochondria and vesicles, the latter electron-lucent in cholinergic axons and with electron-dense cores in adrenergic axons. Within the glands the nerve fibres intermingle, cholinergic and adrenergic axons often lying in adjacent invaginations of one Schwann cell (Eneroth et al 1969, Garrett 1972, 1976).

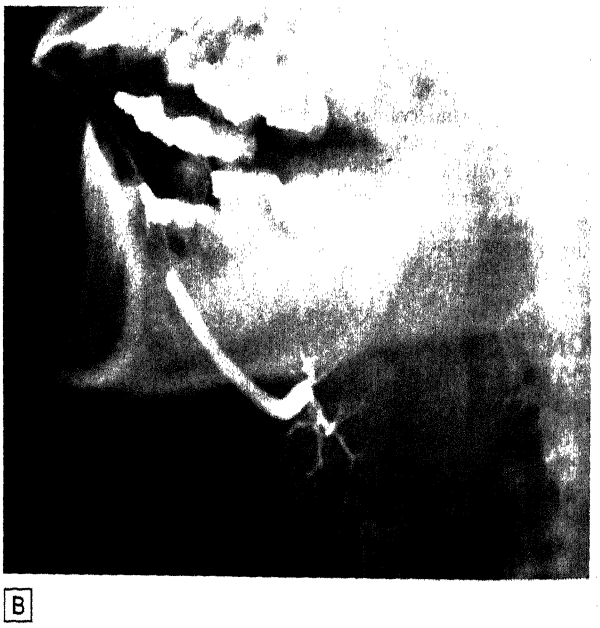
At *neuroeffector junctions* (**12.14**) the synaptic regions of axons and the effector cells they supply are functionally related, the axonal surfaces closest to the effector cells being free of Schwann cell covering. Where effector cells are epithelial, the junctions may be *epilemmal* or *hypolemmal* (Garrett 1975), terms introduced by Arnstein (1889, 1895). At epilemmal sites, the axonal and effector surfaces are separated by about 100 nm, with the basal lamina intervening. At hypolemmal sites the axon penetrates the basal lamina and is separated from the effector cell by only 20 nm. One axon may supply several effector cells directly and many more indirectly through electrical coupling of adjacent cells (Lowenstein & Kanno 1964); group activity thus occurs. One effector cell may also receive several axons, both cholinergic and/or adrenergic. Single axons may act on several types of effector. Although there are separate sympathetic axons for secretion and vasoconstriction (Emmelin & Engström 1960), the former may also induce myoepitheliocyte contraction and a single parasympathetic axon may, through serial neuro-effector junctions of the *en passant* type (p. 1297), induce vasodilatation, secretion and myoepitheliocytic contraction (Emmelin 1972).

Secretory endpieces usually have the most innervation, cholinergic and adrenergic, individual cells often having both. Cholinergic axons have long been accepted as the secretomotor innervation; however, in 1974 it was shown that in the parotid gland of the rat, at least, sympathetic nerves are also secretomotor (Harrop & Garrett 1974, Hodgson & Spiers 1974). Adrenergically evoked saliva differs in quantity and composition but by what mechanism is uncertain. In heterocrine glands adrenergic and cholinergic nerves might activate different types of cell but in homocrine glands (p. 1694), where all cells appear similar, they presumably affect the same cells differently (Garrett 1972). In some situations sympathetic activity may modify saliva produced in response to parasympathetic stimulation, rather than directly inducing flow.

The ductal elements of salivary glands can markedly modify the composition of saliva (p. 1695) and, though less intensely innervated than secretory endpieces, their activity is also under neural influences, in part at least. In 1958 Lundberg showed that cells, assumed to be ductal, in the feline submaxillary gland, responded electrically to both parasympathetic **and** sympathetic stimulation. Cholinergic fibres lie adjacent to the striated ducts of most species, occasionally hypolemmal in position, but more commonly so in intercalated ducts. In some species, including mankind, adrenergic nerves are also associated with striated ducts (Garrett 1967). The main excretory ducts appear to have only cholinergic nerves but Schneyer (1976) observed that sympathetic stimulation alters electrolyte transport across the epithelium of the submaxillary main duct in the rat, suggesting an adrenergic supply.

The innervation of myoepitheliocytes adjoining secretory endpieces and intercalated ducts is physiologically obscure, but electron microscopy suggests a sympathetic and parasympathetic hypolemmal supply (Kagayama & Nishiyama 1972). Myoepitheliocytes are stimulated to contract by adrenergic axons; they may respond to a single

A



B

12.16A, B A. Parotid sialogram; B. Submandibular sialogram. In each case the shadow of the cannula used to introduce the radio-opaque medium into the duct of the gland is visible. See text for description.

impulse, suggesting high sensitivity. The role of cholinergic axons is less certain, but they also may cause contraction (Garrett 1975), thus aiding salivation.

Structural evidence shows that salivary arterioles are innervated by both adrenergic and cholinergic axons (Young & van Lennep 1978). The former, the more numerous, maintain vasoconstrictor tone; the latter may induce vasodilatation but this is maintained by local plasma kinins (see above).

Little information is available on the afferent nerves of salivary glands. Pain due to obstruction of salivary ducts and sialography suggests a nociceptive function, but this awaits anatomical investigation. Sensory endings occur in the main ducts and presumably elsewhere in the glands. Afferent axons are postulated to occur in the main parasympathetic and sympathetic nerve trunks to the glands. Increasing pressure in the submandibular ducts in dogs enhances afferent activity in the chorda tympani (Garrett 1975); intraglandular baroceptors are presumed to be involved in this response. Detailed studies of salivary sensory innervation are clearly needed.

ACCESSORY SALIVARY GLANDS

Besides the main salivary glands many others exist: some in the tongue (p. 1721), others around and in the palatine tonsil between its crypts, with large numbers in the soft palate, the posterior part of the hard palate, the lips and cheeks. These are similar in structure to larger salivary glands and are mainly of the mucous type.

SIALOGRAPHY

Cannulae can be introduced into the parotid and submandibular ducts and used to inject radio-opaque substances (e.g. lipiodol) to outline the ramifications of the ductual systems of these glands, showing their patterns and calibres. The *parotid duct*, as seen in lateral sialograms, is formed near the centre of the posterior border of the mandibular ramus by the union of two ducts which respectively ascend and descend at right angles to the main duct (**12**.16A). As it crosses the face, it also receives from above five or six ductules from the accessory parotid gland; as it curves round the anterior border of the masseter it is often compressed, its shadow being attenuated here. The intraglandular part of the main duct receives an alternating series of descending and ascending tributaries, each formed from an arborization of fine ductules receiving acini. The acini usually do not show as dilatations in sialograms but are represented by the 'free' endings of the smallest ducts. The *submandibular duct* starts from that gland's lowest part, below the mandible in lateral views, ascends vertically above the mandible's lower border and turns sharply forwards, gradually ascending to its opening. The duct's vertical part receives anterior and posterior tributaries and, as it turns sharply forwards, it receives a large tributary from the posterior region (**12**.16B). Each tributary is formed from ductules (with their terminal acini) visualized as in the parotid gland. Contrast medium injected into the submandibular duct may also enter the major sublingual duct, revealing the ductules of the anterior part of the sublingual gland.

TEETH

INTRODUCTION

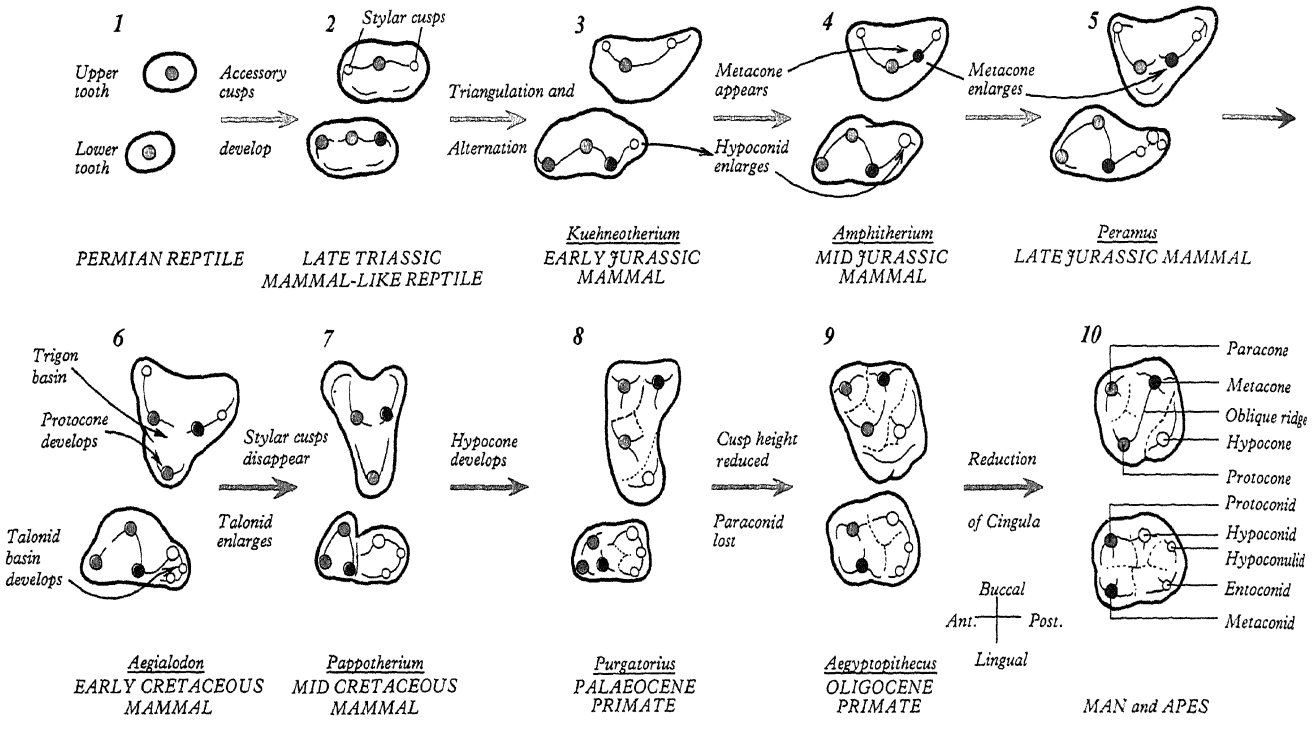
Except in mankind, teeth are necessary for survival in most mammals and other vertebrates, and longevity is related to the endurance of the dentition under the abrasive process of mastication. In non-mammalian vertebrates, teeth are constantly replaced, a condition known as *polyphyodonty*, related to the need for successively larger teeth in animals which grow throughout life. In mammals, where skeletal growth is typically limited to an early period of life, there are generally two dentitions, the first deciduous and the other permanent, the condition of *diphyodonty*; in some mammalian species, e.g. the rat, there is only one set (*monophyodonty*), there being continuous growth of individual teeth. The emergence and success of diphyodonty was probably related to the evolution of occlusion during mastication. In non-mammalian vertebrates, the jaw joint is formed between the quadrate bone of the upper jaw and the articular bone of the lower one, structures homologous respectively with the incus and malleus of mammalian skulls; the lower teeth are also set on a curve so far inside the upper tooth row that, due also to restricted lateral movement, they cannot meet the upper teeth. The evolution of mammals was associated with the posterosuperior growth of the dentary bone (one of several lower jaw elements existing in all non-mammalian vertebrates towards the squamosal, a bone homologous with the squamous temporal in most mammals. In accord with these skeletal changes, the jaw muscles were also rearranged to move the mandible (now formed entirely by the dentary) transversely. Together with these trends there was a change in the shape of the teeth; from the simple conical structures of reptilian ancestors, mammals evolved teeth with complex shearing planes. Lateral movements of the mandible were now possible, allowing the lower teeth to grind across the upper to produce a more effective trituration. Although the deficiencies in the fossil record make some details of this evolutionary process uncertain, the principal stages are known and the cusps of human molars can be homologized with those of early mammals (**12**.17).

After a few months of active use, the newly erupted teeth in mammals are worn to produce precisely matching upper and lower shearing edges. A continued eruption of new teeth would constantly disrupt this relationship and therefore be disadvantageous. However, because of the need to accommodate teeth in small, young jaws, a deciduous dentition is an almost universal requirement in mammals. With this reduction of replacement, dental tissues evolved to minimize the effects of wear. Thus a harder, thicker enamel emerged in mammals, with a prismatic structure which evolved and diversified into a variety of complex and distinctive patterns (Boyde 1976) to resist wear and breakage through fracture, and produce sharp cutting edges.

The teeth in reptiles, apart from some, e.g. the Crocodilia, are firmly attached by bone to the jaws, but in mammals each is suspended in a socket by a periodontal ligament. This flexible system allows adaptive movements of teeth under masticatory loads, and a degree of further eruption (occlusal drift) to compensate for wear; the latter is even more remarkable in species which possess teeth of continuous growth or extended crowns. This suspension also acts as a shock absorber, moderating the effects of transient loads due to mastication on the surrounding bone. Finally, it provides the environment for a rich, spatially ordered periodontal innervation mediating a comprehensive flow of proprioceptive data to nervous centres concerned with control of masticatory patterns.

The introduction of refined carbohydrates in the human diet has made human teeth susceptible to caries and periodontal disease. Outside human culture such dental impairment would probably have led to extinction, but this problem has to some extent been overcome by breaking down, softening or in a sense predigesting food by cooking and other types of culinary preparation. Nevertheless, chewing does facilitate the digestion of most foods, including cooked meat and vegetables (Farrell 1956) and the natural dentition comminutes food much more efficiently than an artificial replacement (Lucas et al 1986). However, teeth are no longer vital to survival and therefore selective pressure leading to further evolutionary change in the human detition will probably be limited.

Because they are the hardest and most stable of tissues, teeth are selectively preserved and fossilized, providing by far the best evolutionary record. Hence teeth are excellent models for studying the relations between ontogeny and phylogeny. In modern societies, the durability of teeth to fire and bacterial decomposition makes



KEY • PARACONE (upper tooth) PARACONID (lower tooth)
• METACONE (upper tooth) METACONID (lower tooth)
• PROTOCONE (upper tooth) PROTOCONID (lower tooth)
HYPOCONE (upper tooth) HYPOCONID (lower tooth)

12.17 Occlusal views of the left upper and right lower teeth showing a series of steps in the evolution of complex molar occlusion. Large cusps (coloured) and smaller cusps are joined together by raised cutting edges. The cutting edges of opposing teeth pass each other during occlusion and certain cusps (e.g. the protocone and hypoconid) then crush into opposing basins (e.g. talonid and trigon basins).

them invaluable in identification of otherwise unrecognizable bodies, a point of great forensic importance (see p. 1720).

General arrangement of dental tissues

A tooth (**12.18–20**) consists of a crown, covered by very hard translucent *enamel* and a root covered by yellowish bone-like *cement*. These meet at the neck or *cervical margin*. A longitudinal section (**12.19, 20**) reveals that a tooth is mostly *dentine* (ivory) with an enamel covering about 1.5 mm thick, while the cement is usually much thinner. The dentine contains a central *pulp cavity*, expanded at its coronal end into a *pulp chamber* and narrowed in the root as a *pulp canal*, opening at or near its tip by an *apical foramen*, occasionally multiple. The root is surrounded by *alveolar bone*, its cement separated from the osseous socket (*alveolus*) by the soft *periodontal ligament*, about 0.2 mm thick. Coarse bundles of collagen fibres, embedded at one end in cement, cross the periodontal ligament to enter the osseous alveolar wall. In most non-mammalian vertebrates (see above) teeth are rigidly connected (ankylosed) directly to bone, a rather brittle attachment. Only in mammals (and Crocodilia) does a periodontal ligament provide an independent, tough suspension for each tooth. Near the cervical margin, the tooth, periodontal ligament and adjacent bone are covered by the *gingiva* (gum), clearly recognizable in health by its pale pink, stippled appearance (**12.21**). This is continuous at the *mucogingival junction* with the red, smooth oral mucosa lining much of the oral cavity and is adherent to the tooth near the cervical margin by an *epithelial attachment*. The pulp is a connective tissue, continuous with the periodontal ligament via the apical foramen. It contains vessels for the support of the dentine and sensory nerves.

DENTAL MORPHOLOGY

The curvature of the dental arches renders the terms of descriptive anatomy, such as anterior and posterior, inappropriate. The aspect of teeth adjacent to lips or cheeks is therefore termed *labial* or *buccal*, that adjacent to the tongue being *lingual* or *palatal*. Labial and lingual surfaces of an incisor meet medially at a *mesial* surface and laterally at a *distal* surface, terms also used to describe the equivalent surfaces of premolar and molar (*postcanine*) teeth (**12.24, 25**). Mesial surfaces of postcanine teeth are, of course, directed anteriorly and distal surfaces posteriorly. Thus the point of contact between the central incisors is the datum point for mesial and distal. The biting or *occlusal* surfaces of postcanine teeth are tuberculated by *cusps* separated by *fissures* forming a pattern characteristic of each tooth. The biting surface of an incisor is the *incisal edge*.

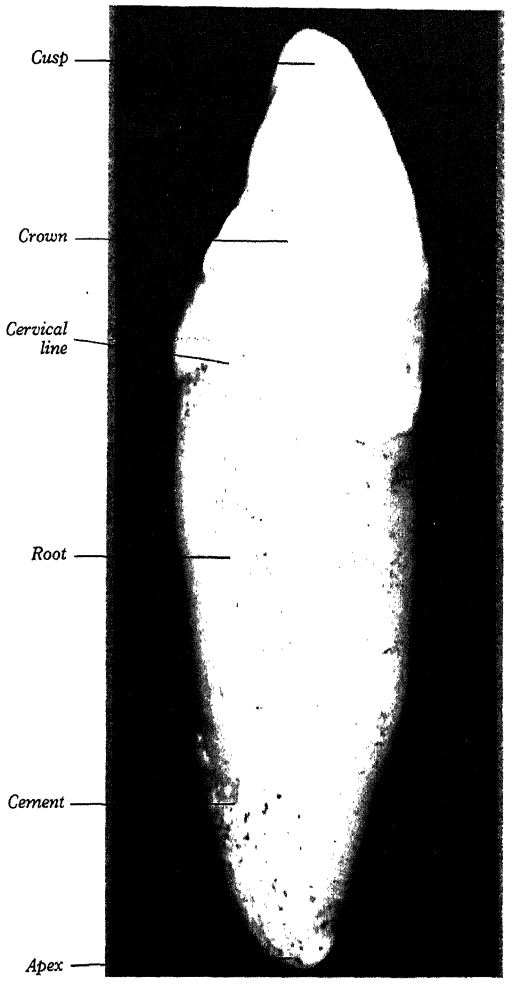
PERMANENT TEETH (12.22, 24, 25, 39)

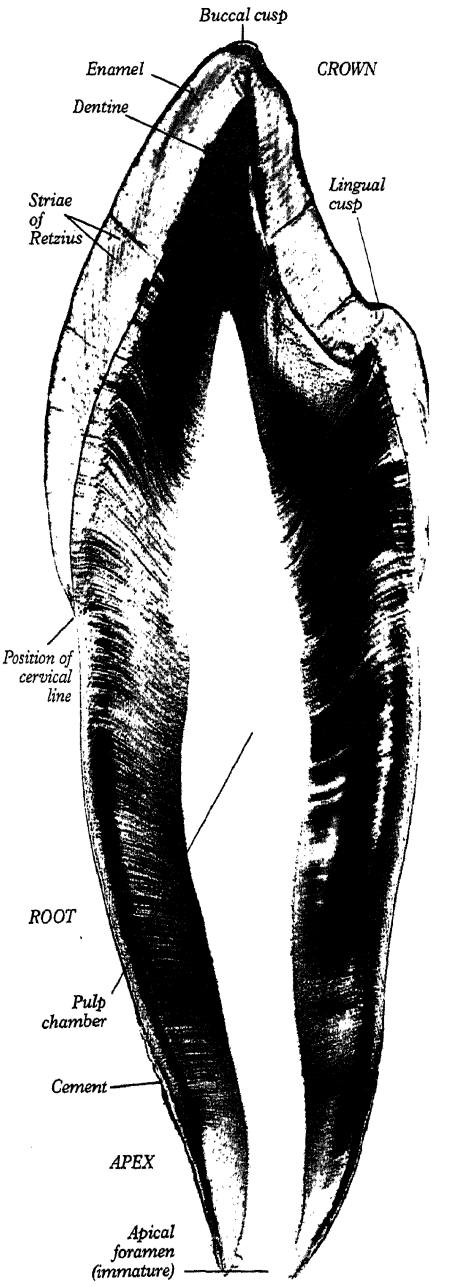
The names for teeth in all mammals are based on the appearance, function or position of the equivalent human teeth: they are the *incisors*, *canines*, *premolars* and *molars*.

There are two incisors, a central and a lateral in each half jaw or *quadrant*. In labial view, the crowns are trapezoid, the maxillary incisor, particularly the central, being larger than the mandibular. The biting or *incisal edges* originally have three tubercles or *mammelons* which are rapidly removed by wear. In mesial or distal view their labial profiles are convex; their lingual surfaces are concavo-convex (ogival); the convexity near the cervical margin is due to a low ridge or *cingulum*, prominent only on upper incisors. The roots of incisors are single and rounded in maxillary teeth, but flattened mesiodistally in mandibular teeth.

Distal to each lateral incisor is a rather larger *canine* with a single cusp (hence the American term *cuspid*) instead of an incisal edge. The lingual cingulum is more prominent in the maxillary than in the mandibular canine. The canine root, which is the longest of any tooth, produces a bulge (*canine eminence*) on the bone externally, particularly in the upper jaw. Although canines usually have single roots, that of the lower may sometimes be bifid (Kraus et al 1969).

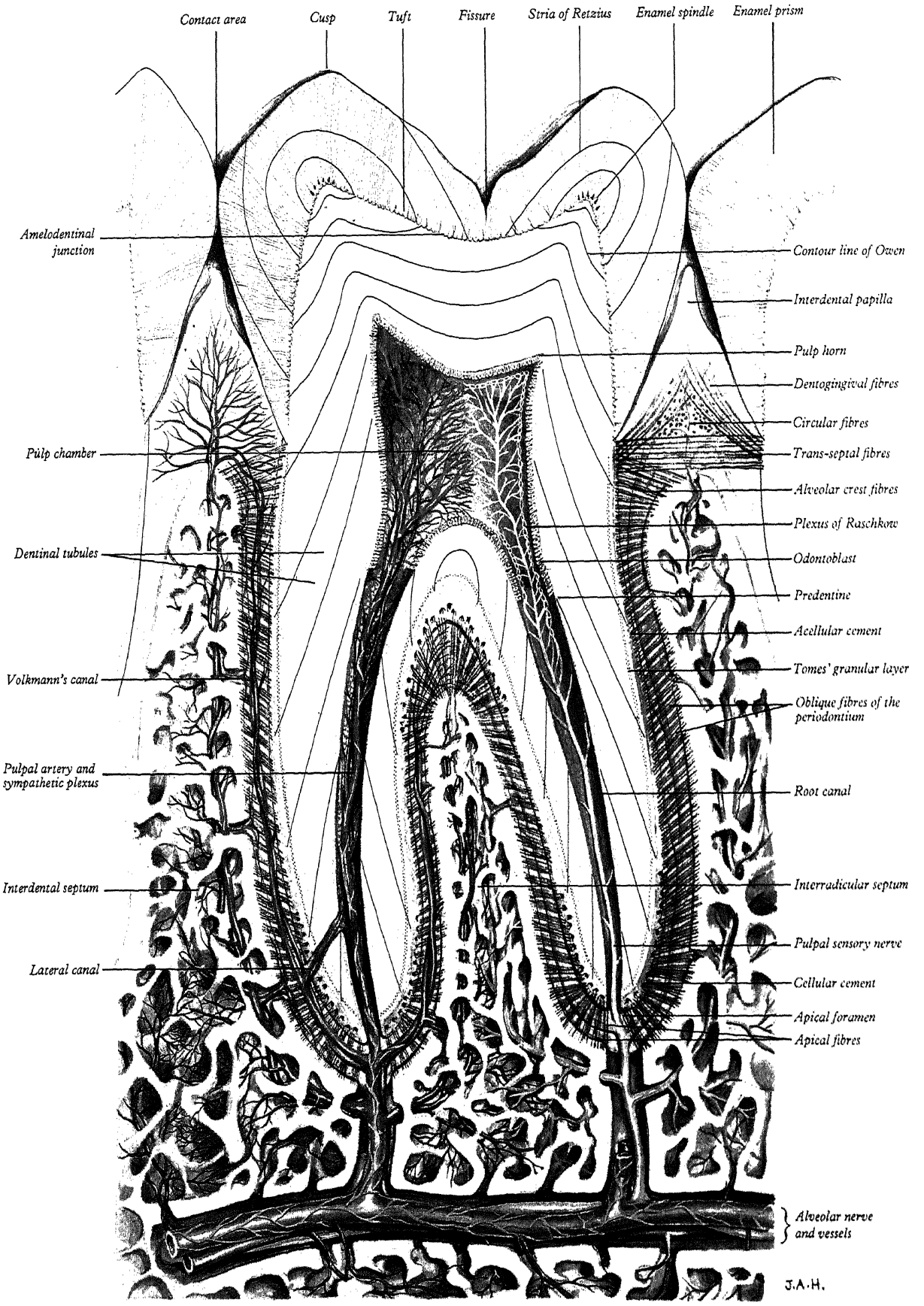
Distal to the canines are two *premolars*, each with a buccal and lingual cusp (hence the term *bicuspid*). The occlusal surfaces of the upper premolars are oval (the long axis is buccopalatal) with a





12.18 An extracted upper right canine tooth viewed from its mesial aspect, showing its principal parts. Note the root covered by cement (partially removed), and the curved cervical margin, convex towards the cusp of the tooth (as also on the distal side of the tooth, not visible here).

12.19 A ground section of a young (permanent) lower first premolar tooth sectioned in the bucco-lingual longitudinal plane, photographed with transmitted light. The coarse dark lines perpendicular to the enamel surface are artefactual cracks caused during grinding of the section; the thinner lines in the enamel running parallel to these cracks indicated the long axes of the enamel prisms. The lines of Retzius are incremental lines of enamel growth (compare with **12.33**). Within the dentine the lines of the dentinal tubules are visible, forming S-shaped curves in the apical region but straighter in the root. The thin layer of cement covering the dentine has been partially removed except where indicated.



12.20 Diagram of a longitudinal section of a tooth and its environs.

mesiodistal fissure separating the two cusps. In buccal view, premolars resemble the canines but are smaller. The *upper first premolar* usually has two roots (one buccal, one palatal) but may have one and very rarely three roots (two buccal and one palatal). The upper second premolar usually has one root. The occlusal surfaces of the lower premolars are more circular or square than those of the uppers. The buccal cusp of the lower first premolar towers above the lingual cusp to which it is connected by a ridge separating the mesial and distal occlusal pits. In the lower second premolar a mesiodistal fissure usually separates a buccal from two smaller lingual cusps. Each

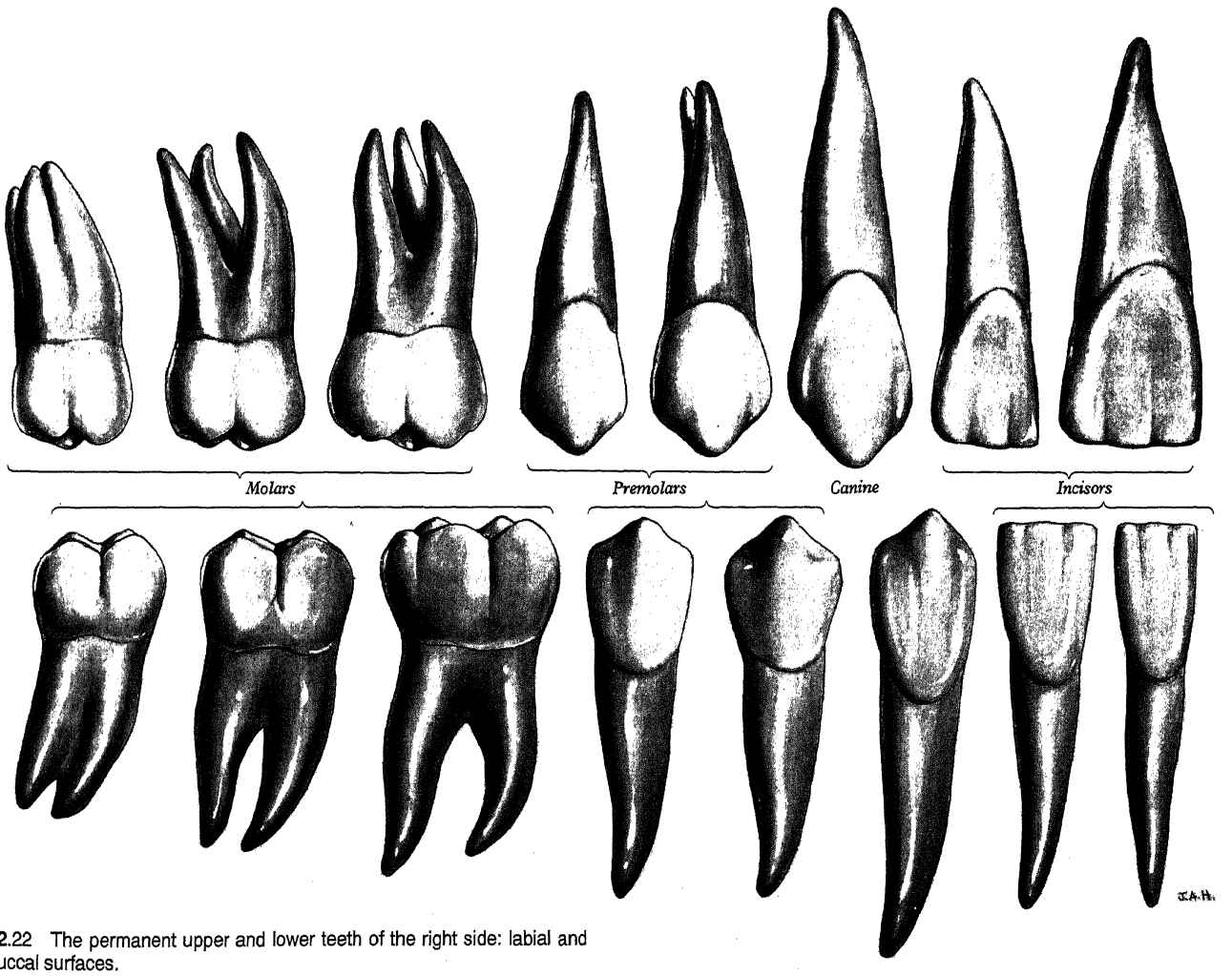
12.21 Anterior view of the dentition in centric occlusion, with the lips retracted. Note the pale pink, stippled gingivae and the red, shiny, smooth alveolar mucosa. The degree of overbite is rather pronounced and the gingiva and its epithelial attachment have receded on to the root of the upper left canine.

lower premolar has one root, but very rarely the root of the first is bifid. Lower second premolars fail to develop in about 2% of individuals (Garn & Lewis 1962).

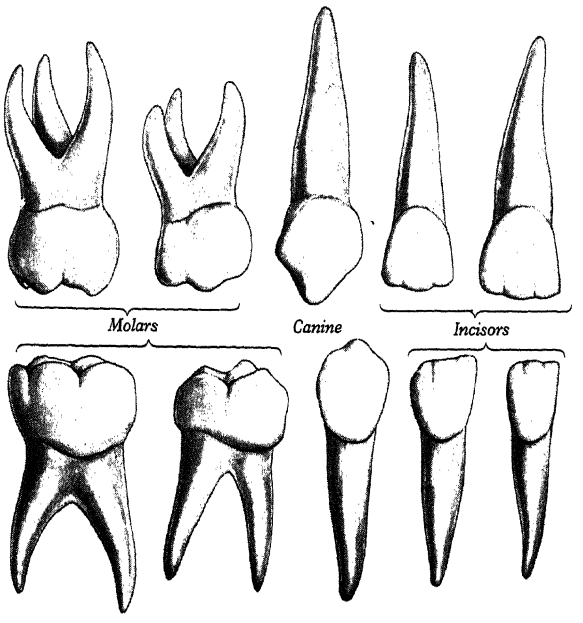
Posterior to the premolars are three *molars* whose size decreases distally; each has a large rhomboid (upper jaw) or rectangular (lower jaw) occlusal surface with four or five cusps. The upper first molar has a cusp at each corner of its occlusal surface and the mesiopalatal cusp is connected to the distobuccal by an oblique ridge, a primitive feature shared with many lower primates. A fifth cusp, the *cusp of Carabelli*, may appear on the mesiopalatal aspect, most commonly in caucasian races (Kraus 1959; Alvesalo et al 1975). The tooth has three widely separated roots, two buccal and one palatal. The smaller *upper second molar* has a reduced or occasionally absent distopalatal cusp; its three roots are divergent and two of them may be fused. The *upper third molar*, the smallest, usually has three cusps (the distopalatal being absent) and commonly one root. The *lower first molar* has three buccal and two lingual cusps on its rectangular occlusal surface, the smallest being distobuccal. The cusps of this tooth are all separated by fissures; it has two widely separated roots, one mesial and one distal. The smaller *lower second molar* is like the first but usually lacks the distobuccal cusp and its (two) roots are closer together. The *lower third molar* is smaller still and like the upper third molar it is variable in form. Its crown may resemble that of the lower first or second molar and its roots are frequently fused. Because it erupts anterosuperiorly it is often impacted against the second molar whereas the upper third molar erupts postero-inferiorly and is rarely impacted. In various populations one or more third molars, upper or lower, fail to develop in 0.2–25% of individuals (Brothwell et al 1963). In general, absence of third molars is commoner in mongoloid and caucasian than in negroid races.

DECIDUOUS TEETH (12.23, 48)

The incisors, canine and premolars of the permanent dentition replace two deciduous incisors, a deciduous canine and two deciduous molars in each jaw quadrant (**12.23**). The deciduous incisors and canine are shaped like their successors but are smaller and whiter



12.22 The permanent upper and lower teeth of the right side: labial and buccal surfaces.



12.23 The deciduous upper and lower teeth of the right side: labial and buccal surfaces.

and become extremely worn in older children. The deciduous molars resemble permanent ones rather than their successors, the premolars. Each second deciduous molar has a crown almost identical to that of the posteriorly adjacent first permanent molar. The *upper first deciduous molar* has a triangular occlusal surface (its rounded 'apex' being palatal) and a fissure separates a double buccal cusp from the palatal cusp. The *lower first deciduous molar* is long and narrow; its two buccal cusps are separated from the two lingual cusps by a zigzagging mesiodistal fissure. Like permanent molars, upper deciduous molars have three roots and lower deciduous molars have two roots; these diverge more than those of permanent teeth since each developing premolar is accommodated directly under the crown of its deciduous predecessor. The roots of deciduous teeth are progressively resorbed by osteoclasts prior to being shed. An extracted deciduous tooth may thus have very short roots.

TOOTH DESIGNATION

Communication between clinicians, often nowadays using computer technology, requires a simple method of indicating each tooth. Unfortunately, no single system is internationally accepted and three methods are currently in use.

The Palmer System uses a horizontal line and a vertical line to partition the dentition into four qudrants and then assigns a number from 1 to 8 to the teeth in each quadrant, beginning with the central incisor:

Right	8 7 6 5 4 3 2 1 | 1 2 3 4 5 6 7 8	Left
	8 7 6 5 4 3 2 1 | 1 2 3 4 5 6 7 8	

Deciduous teeth are indicated by capital letters A–E:

E D C B A	A B C D E
E D C B A	A B C D E

The Universal System, popular in the USA, assigns a unique number to each tooth, beginning with the upper right third permanent molar:

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
32	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17

In the universal system, deciduous teeth are indicated by capital letters, beginning with the upper right second deciduous molar (A) and ending with the lower right second deciduous molar (T).

While the universal system is compatible with information storage and transmission using computer technology, its major disadvantage is the need to memorise a different number or letter for each of the 32 permanent or 20 deciduous teeth. This led the Federation Dentaire Internationale to introduce the Two Digit System. Each tooth is designated by two numbers. The first number indicates the quadrant in which the tooth is situated. In the permanent dentition, the quadrants are numbered 1 to 4 in a clockwise direction when the dentition is viewed from in front and beginning with the upper right quadrant. The second number specifies the individual teeth in a quadrant using the Palmer system. For the deciduous dentition, quadrants are numbered 5 to 8 and the individual teeth in each quadrant are numbered 1 to 5. The two digits which designate each tooth are pronounced separately. Thus in the FDI system the upper right permanent canine is 13 (one-three) and the lower left first deciduous molar is 74 (seven-four).

VARIATIONS IN TOOTH NUMBER, SIZE AND FORM

Variation in number and form, the incidence of which is often related to race, is rare in deciduous teeth but not uncommon in the permanent dentition. One or more teeth may fail to develop, a condition known as *hypodontia*; conversely, additional or *supernumerary* teeth may form, producing *hyperdontia*. The third permanent molar is the most frequently missing tooth: Brothwell et al (1963) found that one or more third molars failed to form in 32% of Chinese mongoloids, 24% of English caucasians and 2.5% of West African negroids. Other missing teeth are, in declining order of incidence, maxillary lateral incisors, maxillary or mandibular second premolars, mandibular central incisors and maxillary first premolars.

Hyperdontia affects the maxillary arch much more commonly than the mandibular dentition (Stafne 1932): the extra teeth are usually situated on the palatal aspect of the permanent incisors or distal to the molars. More rarely, additional premolars develop. Although supernumerary teeth in the incisor region are often small with simple conical crowns, they may impede the eruption of the permanent incisors. A supernumerary tooth situated between the central incisors is known as a *mesiodens*. Teeth may be unusually large (*macrodontia*) or small (*microdontia*). For example, the crowns of maxillary central incisors may be abnormally wide mesiodistally; in contrast, a common variant of the maxillary lateral incisor has a small, peg-shaped crown.

Epidemiological studies reveal that hyperdontia tends to be associated with macrodontia and hypodontia with microdontia, the most severely affected individuals representing the extremes of a continuum of variation. Together with family studies, this indicates that the causation is multifactorial, combining polygenic and environmental influences (Brook 1984).

Some variations in the form of teeth, being characteristic of race, are of anthropological and forensic interest. Mongoloid dentitions tend to have shovel-shaped maxillary incisors with enlarged palatal marginal ridges. The additional cusp of Carabelli is commonly found on the mesiopalatal aspect of maxillary first permanent or second deciduous molars in caucasian but rarely in mongoloid dentitions (Kraus 1959). In negroid races the mandibular second permanent molar often has five rather than four cusps.

DENTAL OCCLUSION

It is possible to bring the jaws together so that the teeth meet or *occlude* in many positions (Kraus et al 1969). When opposing occlusal surfaces meet with maximal '*intercuspation*' (i.e. maximum contact), the teeth are said to be in *centric occlusion* (12.26, 27). In this position the lower teeth are normally opposed symmetrically and lingually with respect to the upper. Some important features of centric occlusion in a normal dentition must be noted. Each lower postcanine tooth is slightly in front of its upper equivalent and the lower canine is in front of the upper. Buccal cusps of the lower postcanine teeth lie between the buccal and palatal cusps of the upper teeth. Thus the lower postcanine teeth are slightly lingual and mesial to their upper equivalents. Lower incisors bite against the lingual surfaces of upper incisors, the latter normally obscuring about one-third of the crowns of the lower. This vertical overlap of incisors in centric occlusion is the *overbite*. The extent to which upper incisors are anterior to lowers is the *overjet*. In the most habitual jaw position

the *resting posture*, the teeth are slightly apart, the gap between being the *free-way space* or *interocclusal clearance*.

Each dental arch is approximately *catenary*, the form of a chain suspended at both ends (MacConaill & Scher 1949), the lower arch being slightly narrower (**12.24**, 25). Viewed from the side, a line joining the buccal cusps of the upper postcanine teeth is curved (*curve of Spee*), concave upwards. The lower molar teeth are tilted slightly lingually so that a line joining the buccal and lingual cusps of the left and right lower first molars is curved (*curve of Monson*), concave upwards. These curvatures accord with movements of the mandible during mastication and are important in the construction of dentures.

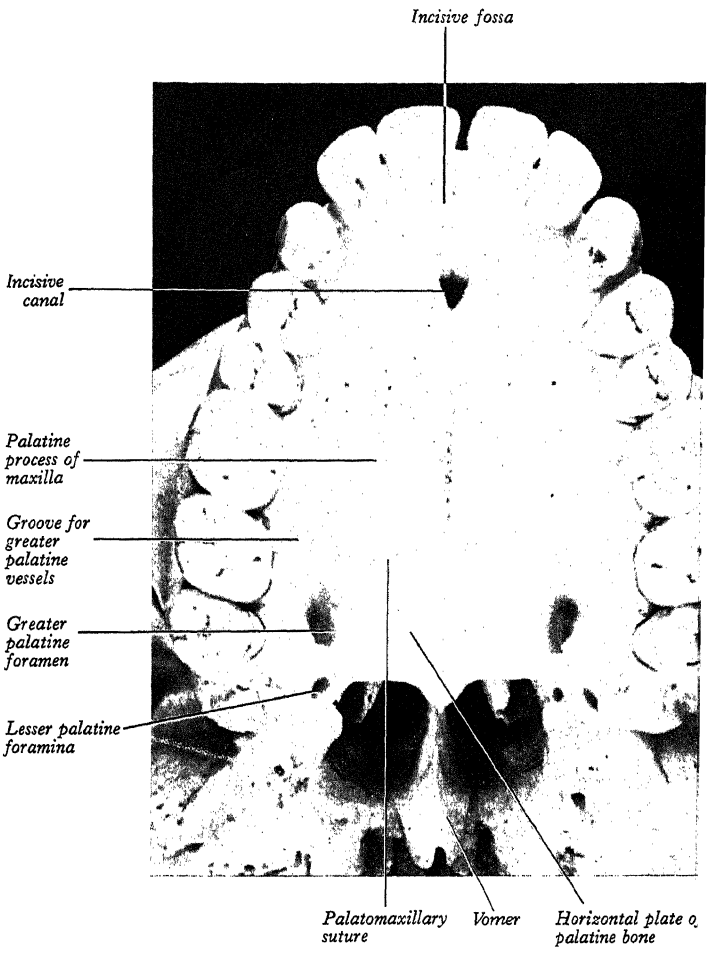
DENTAL BLOOD AND LYMPHATIC VESSELS

The *inferior alveolar artery*, a branch of the maxillary artery, enters the mandibular foramen and travels forwards in its canal to divide into *incisive* and *mental* branches to supply the lower teeth, their supporting structures and the mandibular body, including its cortical bone (Saunders and Röckert 1967). About eight to 12 main rami and variable finer ones supply alveolar bone and teeth (Castelli 1963). Few anastomotic vessels cross the symphysis (Howkins 1935). Veins from alveolar bone and teeth collect either into larger vessels in the interdental septa or into plexuses around the dental apices and thence into several *inferior alveolar veins*; some of these drain through the mental foramen to the facial vein, others via the mandibular foramen to the pterygoid venous plexus (Cohen 1959).

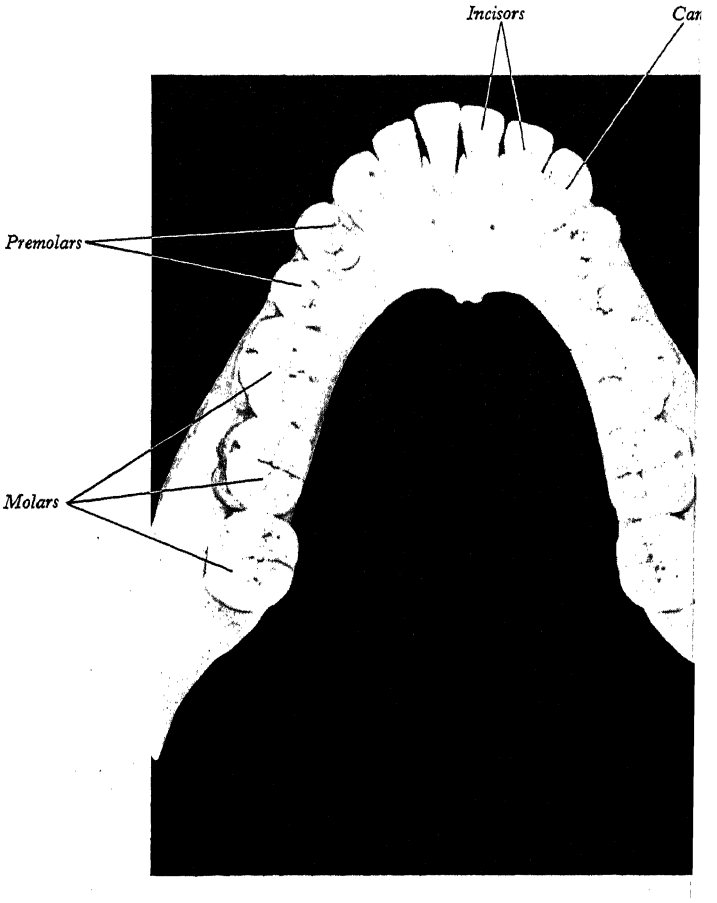
The upper jaw is supplied by *anterior* and *posterior superior alveolar arteries*. The *posterior superior alveolar artery*, from the maxillary artery, gives off branches over the maxillary tuberosity, supplying alveolar bone, mucosa and teeth in the molar region and adjacent buccal mucosa, where they anastomose with the penetrating branches of the facial artery. Other rami supply the lateral wall of the maxillary sinus. The *anterior superior alveolar artery*, a branch of the infraorbital, curves through the *canalis sinuosus* (Jones 1939), which swerves laterally from the infraorbital canal and inferomedially below it in the wall of the maxillary sinus, following the rim of the anterior nasal aperture, between the alveoli of canine and incisor teeth and the nasal cavity; it ends near the nasal septum where its terminal branch emerges. The canal may be up to 55 mm long. Occasionally a small *middle superior alveolar artery* forms anastomotic arcades with the anterior and posterior vessels. On the palatal aspect of the upper teeth, the *greater palatine artery* supplies the palatal gingiva, and its terminal branch ascends through the incisive canal to anastomose with septal branches of the nasopalatine artery. Veins accompanying the superior alveolar arteries drain anteriorly into the facial vein, or posteriorly into the pterygoid venous plexus.

The periodontal ligaments are supplied by *dental branches* of alveolar arteries. One branch enters the alveolus apically and, of its small rami, two or three pass into the dental pulp through the apical foramen, others ascending in the periodontal ligament. *Interdental arteries* ascend in the interdental septa, sending branches at right angles into the ligament, and terminate by communicating with gingival vessels. Thus the ligament receives its blood from three sources: from the apical region, ascending interdental arteries and descending vessels from the gingiva; all anastomose with each other. Veins drain the periodontal ligament either into the *interdental veins* or into the *periapical plexus*. Longer vessels seen in the ligament are probably veins rather than anastomosing arteries (Folke & Stallard 1967).

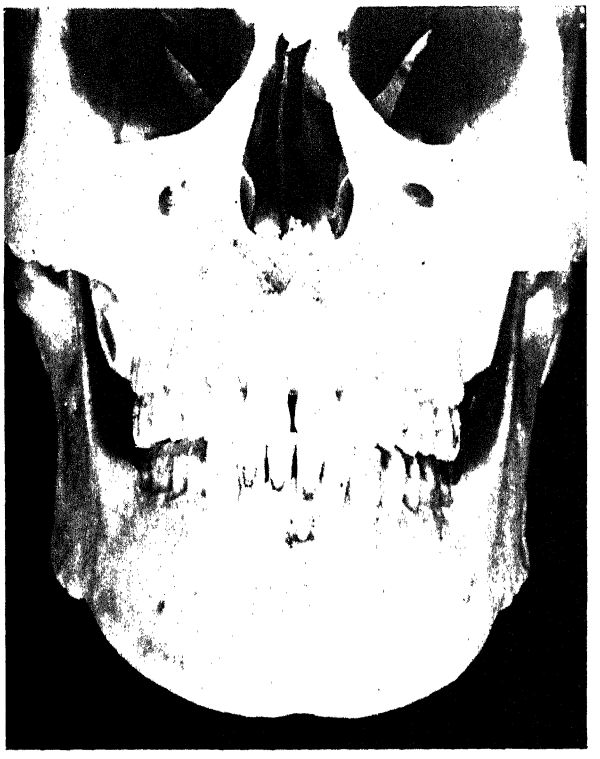
Lymphatic drainage of human jaws and teeth is uncertain (Saunders & Röckert 1967). Injection techniques in monkeys (MacGregor 1936) suggest that the upper jaw drains mainly to the submandibular and thence to supraclavicular lymph nodes, the lower to submental and on to the paratracheal nodes. Many dental abscesses lead to enlargement of the submandibular and upper deep cervical lymph nodes, indicating a common path for lymphatic drainage of the upper and lower teeth. Buccal lymph nodes may be affected by infection of the upper teeth. Lower incisors drain to the submental nodes and thence either to the submandibular or lower



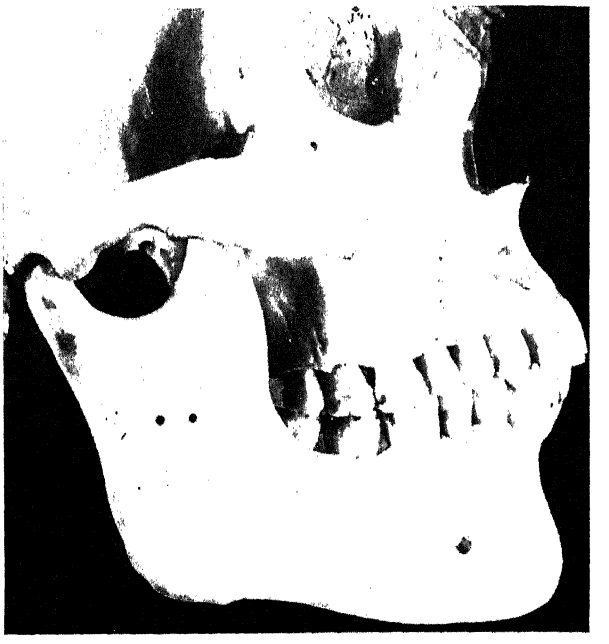
12.24 The permanent teeth of the upper dental arch: inferior aspect.



12.25 The permanent teeth of the lower dental arch: superior aspect.



12.26 Anterior view of the dentition in centric occlusion. There has been some resorption of bone around the lower incisors.



12.27 Lateral view of the dentition in centric occlusion.

deep cervical nodes. It is presumed that the alveolar bone, periodontal ligament and gingiva share the same route.

DENTAL INNERVATION

Upper teeth

These are supplied by the *superior alveolar nerves*, *anterior* and *posterior*; in 80% of individuals a *middle* nerve is also present (Fitzgerald & Scott 1958). These nerves supply a plexus lying above the apices of the teeth, partly on the posterior surface of the maxilla and partly within canals in the lateral and anterior surfaces of the bone (**12.20**). The *buccal nerve* provides a variable contribution to the buccal molar gingiva; the *greater palatine* and *nasopalatine* nerves pass to the palatal gingiva, overlapping in the region of the canine tooth. Surgical division of the nasopalatine nerve causes no obvious sensory deficit in the anterior palate, suggesting that the territory of the greater palatine nerve reaches as far forwards as the gingiva lingual to the incisor teeth (Langford 1989).

The *posterior superior alveolar nerves* are two or three trunks from the postorbital section of the maxillary nerve (**8.339**). They divide into several rami within the periosteum and enter widely scattered foramina on the maxilla's posterior surface. Higher branches descend outside the antral mucosa to meet lower branches passing forwards above the teeth. The variable *middle alveolar nerve*, which may branch anywhere along the orbital part of the maxillary nerve, runs down the antral wall; the *anterior alveolar nerve* occupies the *canalis sinuosus* (p. 1705). The bony canals of the superior alveolar nerves also contain corresponding arteries forming the *superior alveolar neurovascular bundles*.

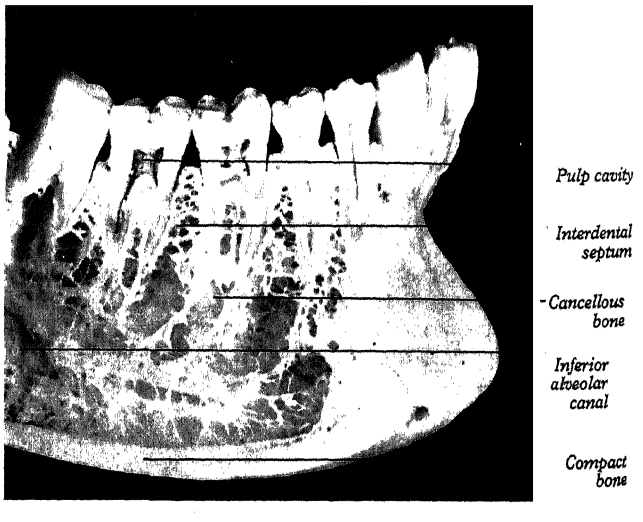
Lower jaw and its alveolar bone

These are largely supplied by the *inferior alveolar nerve*, with branches of the *buccal nerve* to the buccal gingiva of the molar and premolar teeth and branches of the *lingual nerve* to the lingual gingiva of all the lower teeth.

In its commonest form (six out of eight mandibles studied by Carter & Keen 1971), the inferior alveolar nerve is single, travelling through a well-defined osseous canal close to the dental roots (**12.28, 39**), supplying individual branches to these and the interdental septa. Between the premolar teeth the mental nerve, often multiple, leaves via the mental foramen. Intraosseous *incisive nerves* continue to supply the first premolar, canine and incisor teeth. Branches leave the mental nerve at its origin to form an *incisor plexus* labial to the teeth, probably supplying their labial periodontium and gingiva. From this plexus and the dental branches, rami turn down and then lingually to emerge on the lingual surface of the mandible on the posterior aspect of the symphysis or opposite the premolar teeth, probably communicating with the lingual or mylohyoid nerve.

Less commonly (two out of eight mandibles in the above study), the inferior alveolar nerve was close to the lower border of the mandible, well below the roots of the teeth (**12.28**) with a variable number of large rami passing anterosuperiorly towards the roots before dividing to supply the teeth and interdental septa.

In three out of eight dissected mandibles nerves passed from the temporal muscle to enter the mandible through the retromolar fossa, communicating with branches of the inferior alveolar nerve. Foramina occur in about 10% of retromolar fossae (Azaz &



12.28 Anterior part of the right mandible, with the superficial bone removed on the buccal side to show the roots of a number of teeth, some of which have also been sectioned vertically. Note: the cortical plate of compact bone lining the sockets of the teeth (the lamina dura of radiographs: see **12.50–53**), and the flat table of bone surmounting the interdental bone septa. In this specimen the inferior alveolar canal is widely separated from the roots of the teeth, a variable condition.

Lustmann 1973) and infiltration in this region can abolish sensation, occasionally remaining after an inferior alveolar nerve block. Similarly, branches from the buccal, mylohyoid and lingual nerves which enter the mandible may provide additional routes of sensory transmission from the teeth.

The lower central incisor teeth receive a bilateral innervation, fibres probably crossing the midline within the periosteum to re-enter the bone via numerous canals in the labial cortical plate (Rood 1977).

Local and regional analgesia

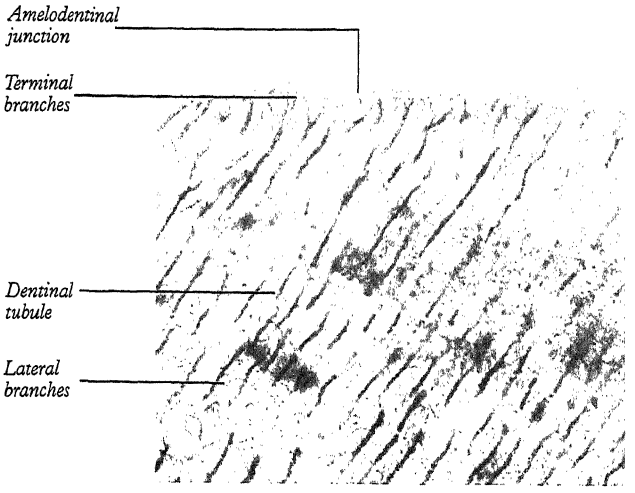
For restorative procedures, it is sufficient to block conduction in nerves supplying the pulp of a tooth; but for surgical operations on the jaws, such as the extraction of teeth, it is also necessary to obtain analgesia of their supporting tissues: the alveolar bone, gingiva and periodontal ligament. In the upper jaw, where the outer alveolar bone is thin, analgesia of teeth as well as the labial and buccal periodontium is achieved by local infiltration of an anaesthetic solution into the submucosa of the sulcus adjacent to the root apices. In extracting maxillary teeth, analgesia of palatal alveolar bone and gingiva requires a submucosal infiltration next to the tooth on its palatal aspect or blockage of the greater palatine or nasopalatine nerves near the foramina where they enter the oral cavity.

Pulpal analgesia of mandibular incisors and canines can be obtained by submucosal infiltration in the labial sulcus; an infiltration on the lingual aspect will complete analgesia of the supporting tissues when extracting these teeth. Because the alveolar bone supporting the mandibular premolars and molars is thick, particularly on the buccal aspect, local infiltration is not effective in producing pulpal analgesia and a regional block of the inferior alveolar nerve is required. With the mouth wide open and the syringe directed from the region of the contralateral premolar teeth, the needle penetrates the mucosa and buccinator muscle immediately anterior to the stretched pterygomandibular raphe, and anaesthetic solution is deposited around the inferior alveolar nerve just above the mandibular foramen. An aspirating syringe is recommended to prevent accidental injection into nearby blood vessels. In the majority of cases, such a regional block will produce pulpal analgesia of all mandibular teeth on the injected side of the jaw, apart from the central mandibular incisor which is usually partly supplied by fibres from the contralateral nerve. However, because of individual variations in the nerve supply of teeth (see above), buccal and lingual infiltrations adjacent to the operative site may be needed to obtain full pulpal analgesia. For tooth extraction, when analgesia of the lingual alveolar bone and mucosa is essential, the lingual nerve can be blocked as it runs anteromedial to the inferior alveolar nerve. Additionally, an injection is required in the buccal sulcus to prevent conduction in the buccal nerve.

DENTAL HISTOLOGY

DENTINE (12.18–20, 29–31, 33, 34, 39)

Dentine is yellowish avascular tissue forming the bulk of the tooth. It is a tough (work of fracture, Wf = 270–550 J/m^2) and compliant (stiffness = 12 GN/m^2) composite material, about 70% by weight mineral (largely crystalline hydroxyapatite and fluorapatite but some calcium carbonate) and 20% organic matrix (type I collagen fibres, glycosaminoglycans and phosphoprotein, Weinstock & Leblond 1973). Its conspicuous feature is the regular pattern of microscopic dentinal tubules, about 1–2 μm in diameter, extending from the pulpal surface (about 50 000 tubules per 1 sq mm cross-sectional area) to the enamel–dentine junction (about 20 000 per sq mm). Tubules have a single sinuous primary curvature (**12.19**) oriented apically and more pronounced in the crown. A spiral secondary curvature, less regular, has a periodicity and amplitude of a few microns. Near the enamel–dentine junction tubules bifurcate, some with short extensions into enamel. Abundant lateral branches interconnect adjacent tubules (**12.29**). Each tubule encloses a single cytoplasmic process of an odontoblast, containing microtubules, microfilaments but few ribosomes or mitochondria. Odontoblast cell bodies are in a pseudostratified layer lining the pulpal surface. In newly erupted teeth, processes are believed to extend the full thickness

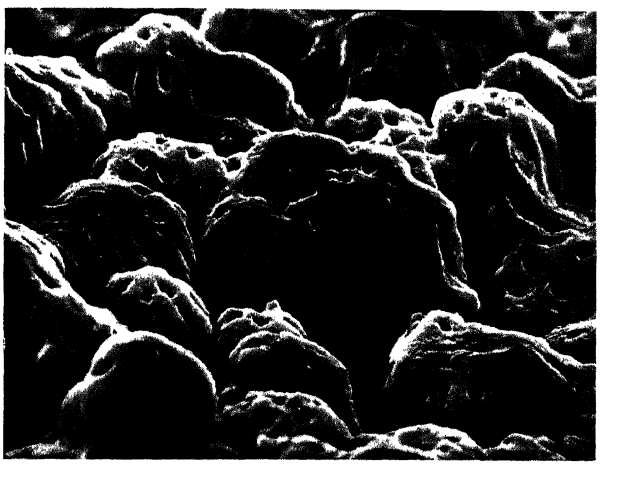


12.29 A demineralized section of dentine, cut in the plane of the dentinal tubules, showing their lateral and, near the amelodentinal junction, terminal branching. Magnification ×600. (Provided by D. Luke, Department of Anatomy and Cell Biology, UMDS, Guy's Campus, London.)

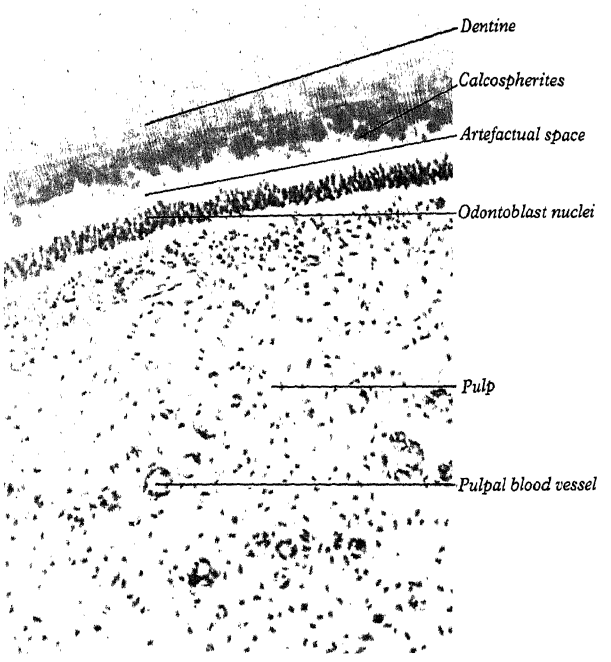
of dentine (Sigal et al 1984; Holland 1985) but in older teeth may be partly withdrawn so as to occupy only the pulpal third, the outer regions containing extracellular fluid (Thomas 1979). Lining most tubules is a heavily mineralized cylinder of peritubular dentine, devoid of collagen fibres, separated from the plasma membrane of the process by a glycosaminoglycan-rich lamina limitans (Thomas & Carella 1983). It is uncertain whether the process directly abuts the lamina limitans or whether there is a fluid-filled periodontoblastic space separating them.

Between the odontoblasts and the dentine is a layer of non-mineralized matrix, the *predentine* (**12.30, 31**). The predentine–dentine border is irregularly scalloped (**12.30**) because dentine mineralizes as microscopic spherical aggregates of crystals (calcospherites). The enamel–dentine junction is more regularly scalloped, with convexities towards the dentine, a pattern unrelated to mineralization. Next to the enamel–dentine junction is a 30–40 μm layer (mantle dentine) which is less mineralized and has collagen fibres arranged parallel to the tubules. In the remaining circumpulpal dentine, fine collagen fibres are perpendicular to and interwoven around the tubules.

Dentine, like enamel is deposited incrementally and is not remodelled. Both tissues carry a permanent record of changing shape, rhythmical formation and disturbances during development. The nomenclature of the resulting pattern of lines seen in sections of dentine has been revised by Dean et al (1993) and is used here. Fine *incremental lines of von Ebner*, 2–5 μm apart in the bulk of dentine, record diurnal alterations in the orientation of collagen fibres and



12.30 Surfaces of calcospherites. The holes (about 1 μm wide) are dentinal tubules. (Provided by D Whittaker, The Dental School, University of Wales, Cardiff.)



12.31 Section of a demineralized tooth showing the junctional region between the pulp and dentine, sectioned parallel to the plane of the dentinal tubules. Haematoxylin and eosin. For details see text.

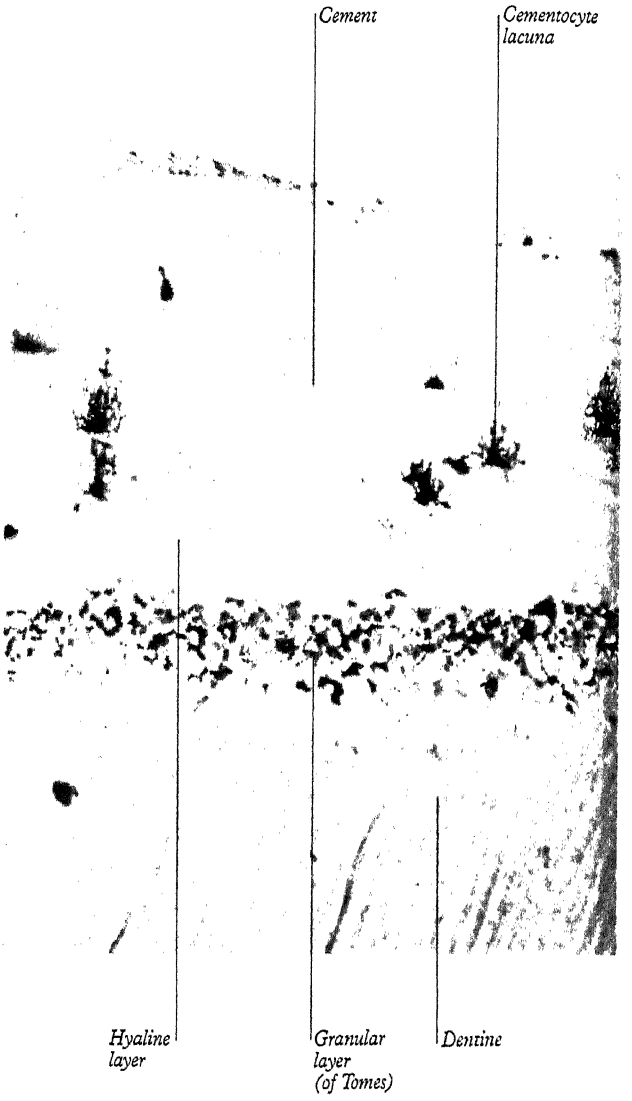
levels of mineralization. Longer periodicity lines, 15–30 μm apart, occur at intervals of 6 to 10 days. These are now referred to as *Andresen lines* and are equivalent to the Retzius lines in enamel. A third type, at irregularly spaced intervals, is due to the coincidence of slight variations in direction of the dentinal tubules. These *contour lines of Owen* do not represent incremental growth but probably reflect minor disturbances in tooth formation due to illness or malnutrition. As in enamel, a prominent feature is formed in dentine where mineralization spans birth (all deciduous teeth and usually the first permanent molars); this is the *neonatal line*, a result of the associated abrupt changes in environment and nutrition. During dentinal development, failure of fusion of calcospherites produces interglobular areas. Often regarded as evidence of defective dentinogenesis, they are so common in a region 100–300 μm from the enamel–dentine junction that they must be considered normal.

The outermost 10 μm of root dentine, the hyaline layer (Owens 1972), may incorporate enamel matrix proteins secreted by the epithelial root sheath (Schonfeld & Slavkin 1977). Internal to this is the granular layer of Tomes (**12.32**), whose granularity may be due to minute interglobular areas or to small terminal expansions and anastomoses of adjacent odontoblast processes (Ten Cate 1972).

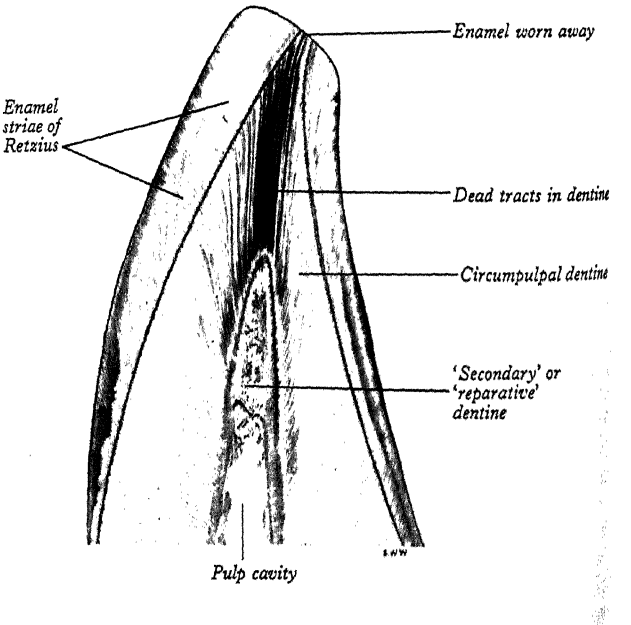
Primary dentine formation proceeds at a steady but declining rate as first the crown and then the root is completed. Further reduction in the size of the pulp chamber continues throughout life with the very slow and intermittent deposition of secondary dentine, sometimes distinguished from primary dentine by an Owen line and by a sudden change in direction of dentinal tubules. If dentine receives a severe stimulus (e.g. rapidly advancing caries or wear, tooth breakage) the odontoblasts of the affected region die, leaving a dead tract. This is sealed pulpally by a thin zone of sclerosed dentine and the deposition by newly differentiated pulp cells of reparative dentine, a poorly mineralized and sporadically formed tissue with few and irregular tubules. A less severe stimulus results in the odontoblasts increasing the deposition of peritubular dentine so as to fill the tubules. In ground sections this dentine appears translucent because it has assumed a near-uniform refractive index. Translucent dentine also develops with age near the root apices.

DENTAL PULP (12.20, 31, 33, 34, 39)

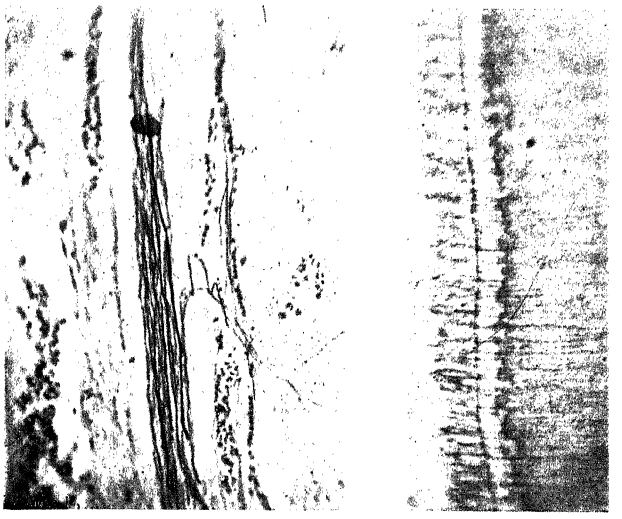
The pulp is a well-vascularized volume of loose connective tissue, enclosed by dentine. It is continuous with the periodontal ligament via the apical and accessory foramina. Several thin-walled arterioles



12.32 Ground, unstained longitudinal section of the root of a tooth, showing the cementum and superficial dentine. Note in the cementum the dark lacunae with projecting canaliculi, originally occupied by cementocytes and their processes. Magnification × 800. (Provided by D. Luke, Department of Anatomy and Cell Biology, UMDS, Guy's Campus, London.)

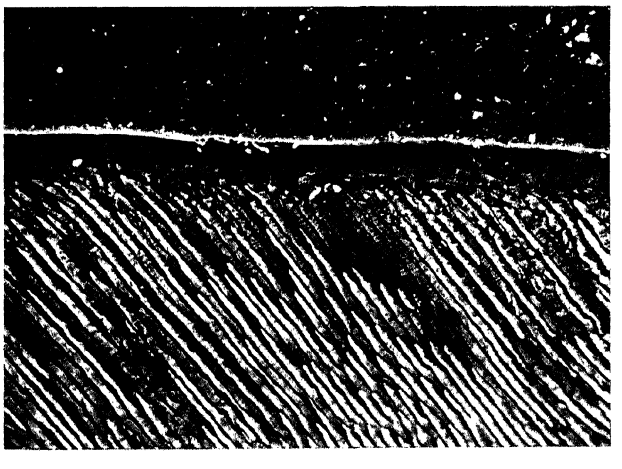


12.33 Longitudinal ground section of an incisor tooth. Compare the brown striae labelled on this section with those visible on **12.19**.

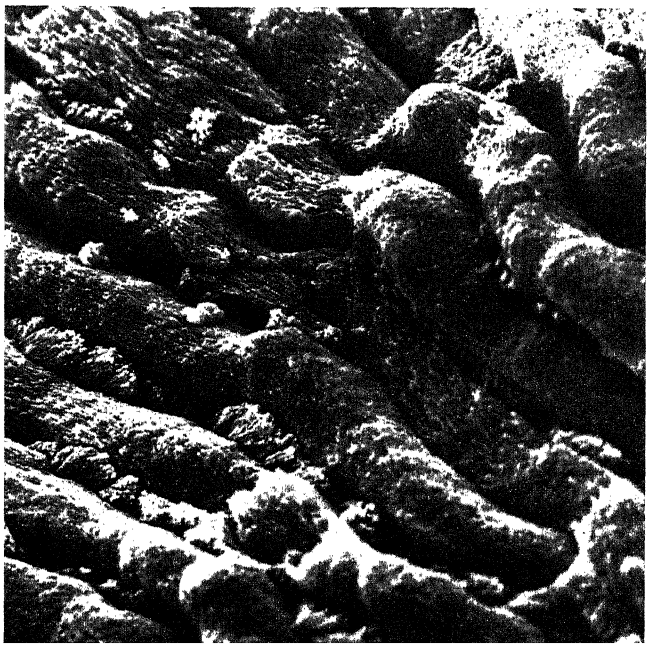


12.34 Longitudinal demineralized section of a tooth stained with a silver impregnation technique. Note the vertical nerve trunk (left of centre) within the pulp, with fine nerve fibres, one of which crosses transversely to pass between the odontoblasts lining the surface of the predentine (the pale-staining vertical layer, right of centre).

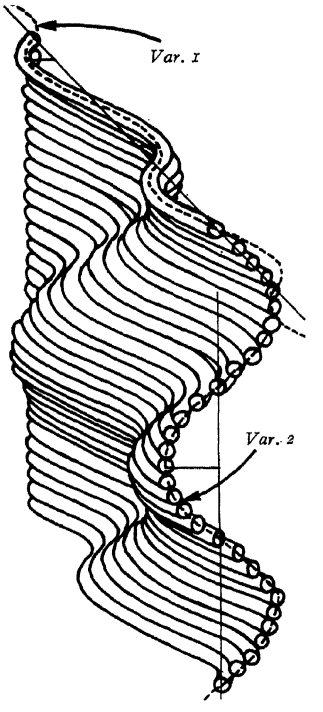
enter by the apical foramen to run longitudinally, giving branches to an extensive subodontoblastic plexus (Takahashi et al 1982). Capillary loops may also occur in the odontoblast layer. Blood flow, in terms of rate per unit volume, is greater in the pulp than in other oral tissues (Kim 1990). Micropuncture measurements of interstitial fluid pressure (5–8 mmHg) indicate that it is much lower than hitherto supposed (Tonder & Kvinnsland 1983). Several small veins and lymphatic vessels (Bernick & Patek 1969) emerge from the pulp. Unmyelinated postganglionic sympathetic nerve fibres from the superior cervical ganglion enter the pulp with the arterioles. Myelinated (Aδ) and unmyelinated (C) sensory nerve fibres from the trigeminal ganglion traverse the pulp longitudinally (**12.34**) giving branches to ramify in the *plexus of Raschkow* (Scheinin & Light 1969) in the cell-rich parietal zone. Here fibres lose their myelin sheaths and continue into the odontoblast layer, some entering the dentinal tubules. Intratubular nerves are distinguishable from odontoblast processes because the former contain many mito-



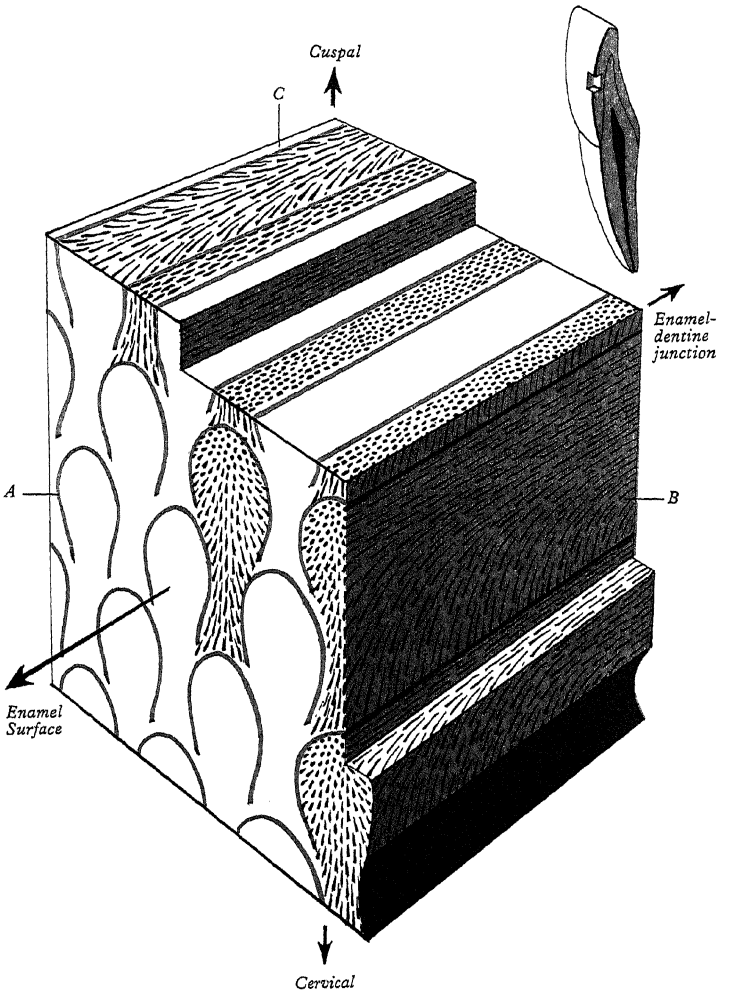
12.35A Scanning electron micrograph of enamel prisms. Each prism is about 5 μm wide and separated from adjacent prisms by interprismatic material which has been removed from this specimen by acid etching. A thick structureless surface layer is present. (Provided by D Whittaker, The Dental School, University of Wales, Cardiff).



12.35B Scanning electron micrograph of the surface of fractured enamel at a higher magnification than **12.35A**. The rope-like prisms run approximately parallel to each other and show periodic variations in thickness, representing daily growth increments. Abrupt alterations in the direction of individual prisms are responsible for the appearance of the striae of Retzius. (Provided by D Luke, Department of Anatomy and Cell Biology, UMDS, Guy's Campus, London.)



12.36 Diagram illustrating the relationships existing between a vertical stack of enamel prisms. Each prism undulates in the transverse plane of the tooth but its undulations are out of phase with those of vertically adjacent prisms. Hence, when a section is viewed by reflected light, the undulations are responsible for the characteristic alternation of dark and light bands which cross the prisms obliquely (the Hunter-Schreger bands). Var. 1 and 2 indicate the sine-wave undulations in the transverse and vertical planes, which vary in amplitude and periodicity in the enamel of different species. (From Osborn 1973 with permission of the author and publishers, Springer.)



12.37 Diagram of a block of enamel showing how the orientation of the crystallites determines their appearance when the prisms are cut transversely (face A), longitudinally (face B) or at right angles to both these planes (face C). Prism boundaries or sheaths (blue) are formed wherever crystallites meet at highly discordant angles. Superimposed on the transversely cut face (A) are cross-sectional outlines of the ameloblasts (yellow).

12.38 Scanning electron micrograph of the enamel surface showing perikymata. The holes (about 4 μm wide) were occupied by Tomes' processes of ameloblasts when the development of the enamel was completed. (Provided by D Whittaker, The Dental School, University of Wales, Cardiff.)

chondria (Frank 1968); they are more numerous beneath the cusps (where one in four tubules is occupied) than elsewhere (Lilja 1979). Ultrastructrual studies have failed to show nerve fibres beyond 100 μm into human dentine but autoradiography of rats' teeth following injection of tritiated proline into the trigeminal ganglion and axonal transport of labelled proteins has revealed innervation in dentinal tubules near the enamel–dentine junction (Pimendis & Hinds 1977).

Stimulation of dentine, whether by thermal, mechanical or osmotic means, evokes a pain response. The mechanism of stimulus transduction is unknown but is unlikely to involve the direct stimulation of nerve endings in dentine. Newly erupted teeth are sensitive yet do not have a plexus of Raschkow, although, in contrast to earlier studies, some nerve fibres have been found in dentinal tubules before tooth eruption (Byers 1984). Pain-producing chemicals and local anaesthetics show little ability to stimulate or anaesthetize exposed dentine. One possibility is that the odontoblast process can propagate some kind of impulse and excite nerve endings in contact with the proximal part of the process or the cell body. But neither synapses nor gap junctions have been definitely identified between nerves and odontoblasts; although their cell membranes occasionally come into close approximation, the nature and functional significance of such junctions are unknown (Sessle 1987). An alternative hypothesis suggests that stimuli generate movement of intracellular fluid or extracellular fluid along the dentinal tubules, causing in turn a local distortion of the pulp, sensed by free nerve endings in the plexus (Brännström 1963; Anderson et al 1970). Evidence that odontoblasts are joined together by continuous tight junctions (Bishop 1985) suggests that the odontoblast may be directly involved in relaying intratubular fluid movements to nerve endings. This 'hydrodynamic' theory would explain the ineffectiveness of neuroactive agents and why pain is produced by drying and by solutions of high osmotic pressure. Solutions equally effective in producing pain, however, create very different rates of flow (Anderson & Matthews 1967; Horiuchi & Matthews 1973).

ENAMEL (12.19, 20, 33, 35–38)

Enamel (Osborn 1973; Boyde 1989) is an extremely hard (Knoop number = 300+) and rigid (stiffness = 40–80 GN/m^2) material covering the crowns of teeth. It is a heavily mineralized cell secretion, containing 95–96% by weight crystalline apatites (88% by volume) and less than 1% organic matrix. Since its formative cells are lost from the surface (12.38) during eruption, it is incapable of further growth; repair is limited to the remineralization of minute incipient carious lesions. It reaches a maximum thickness of 2.5 mm over cusps and thins to knife edge at the cervical margins. Enamel is composed of closely packed enamel *prisms* (or rods), U-shaped in cross section (12.37), extending from close to the enamel–dentine junction to within 6–12 μm of the surface. Each prism is partially delineated by a matrix-rich *prism sheath*, 70 nm thick, and is separated from neighbouring prisms by a continuous *interprismatic region*. Prisms are about 3–4 μm wide in inner enamel, increasing to about

6 μm near the surface. Prisms are packed with flattened hexagonal hydroxyapatite crystallites, 26 nm × 68 nm in cross-section (Daculsi & Kerebel 1978). Hexagonal transverse profiles of ribbon-like crystallites are randomly oriented. In the cuspal region of a prism (plane C in **12.37**) these are almost parallel to the prism's long axis and may be as long as the enamel is thick (i.e. up to 2.5 mm); but in the cervical region of a prism (plane B in **12.37**) and in interprismatic regions, the crystallites have a pronounced cervical inclination and end at the cervically-adjacent prism sheath. A sudden change always exists between crystallite orientation on the two sides of a prism sheath. In surface enamel, crystallites are packed with their long axes parallel so that prism sheaths do not form.

At intervals of about 4 μm along its length, each prism is crossed by a dark *striation*, the light microscope manifestation of a rhythmic swelling and shrinking of prism diameter during one day's growth. Higher order incremental lines in enamel are *striae of Retzius* (**12.20**), passing from the enamel–dentine junction obliquely to the surface where they end in shallow furrows, *perikymata*, visible on newly erupted teeth (**12.38**). Each stria represents a period of 7–8 days' enamel growth (Bromage & Dean 1985). Striae are produced by a sudden double right-angle translocation of the prisms in the longitudinal plane and may be clear or brown in transmitted light. Tyndall scattering of short wavelengths is due to accumulations of matrix in the prism translocations. A prominent stria, the *neonatal line* (Whittaker & Richards 1978), is formed in teeth whose mineralization spans birth. Neonatal lines in enamel and dentine are of forensic importance, indicating that an infant has survived for a few days.

Each prism is sinuous in the tooth's transverse plane with a wavelength of about 1.5 mm, undulations of one prism being matched by those lateral to it but slightly (2°) out of phase with those above or below (**12.37**). Prism sheaths are comparatively weak interfaces in enamel (work of fracture, Wf = 200 J/m^2 perpendicular to prisms but only 13 J/m^2 parallel to prisms; Waters 1980). Decussation of prisms in the tooth's longitudinal plane is an adaptation which increases the toughness of enamel by enlarging the surface area of potential cracks between prisms in that plane. Similar regular undulations over cusps produce the appearance of gnarled enamel in sections.

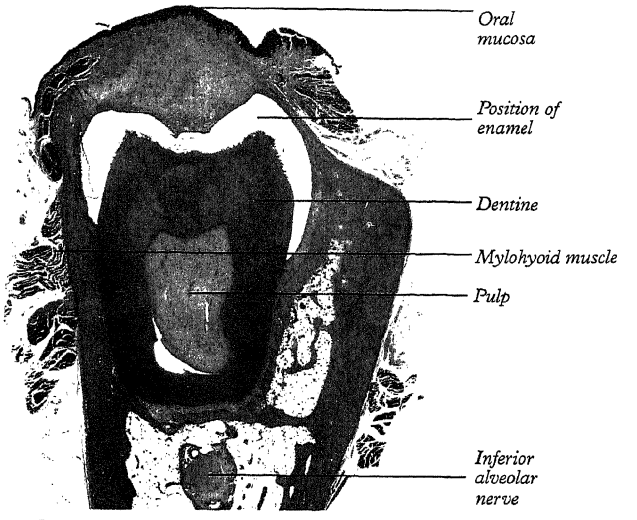
Prism sheaths in the inner enamel are considerably thickened to form tuft-like projections from the enamel–dentine junction, extending for a considerable distance in the longitudinal plane of the tooth. Longitudinal sheets of organic material penetrating the full thickness of enamel are *enamel lamellae*. Extensions into the enamel of dentinal tubules are *enamel spindles*, prominent over cusps.

CEMENT (12.18–20, 32, 40)

Cement is a bone-like tissue covering the dental roots, about 50% by weight hydroxyapatite and amorphous calcium phosphates (Frank & Steuer 1977). In newly erupted teeth, the cement generally overlaps the enamel slightly but may just meet the cervical margin or fall short, leaving dentine exposed at the periodontal ligament. All three situations may prevail around the neck of a single tooth. In older teeth, when the root becomes exposed in the mouth through occlusal drift and gingival recession, cement is often worn away and dentine revealed.

Cement is perforated by *Sharpey's fibres*, attachment bundles of periodontal ligament collagen fibres (extrinsic fibres). New layers of cement are deposited incrementally throughout life to compensate for tooth movements, incorporating new Sharpey's fibres. Incremental lines (of Salter) are irregularly spaced.

The first formed cement is thin (up to 200 μm), acellular and contains only extrinsic fibres; but cement formed later is produced more rapidly and contains cementocytes in lacunae joined by canaliculi mainly directed towards the periodontal ligament. This cement contains both extrinsic fibres and matrix (intrinsic) fibres of cementoblastic origin. With increasing age cellular cement may reach a thickness of a millimetre or more around the apices and at the furcations of the roots, where it compensates for the loss of the periodontal attachment area through occlusal drift. Cement is not usually remodelled but will repair both small areas of resorption and fractures of the dentine. Cement deposition within the apical foramen is a cause of vascular strangulation of the pulp which progresses with age.



12.39 Section through the body of the mandible and associated soft tissue, demineralized and cut in the coronal plane. An unerupted third permanent molar tooth is visible in this section. The buccal side is to the right. Note that decalcification prior to sectioning has removed the enamel, whose position is represented by an empty space outlined by the juxtaposed tissues. Magnification × 3.5. (Provided by D. Luke, Department of Anatomy and Cell Biology, UMDS, Guy's Hospital, London. Photographed by Sarah Smith, Division of Anatomy, Guy's Hospital, London.)

PERIODONTAL LIGAMENT (MEMBRANE) (12.20, 39)

The periodontal ligament (Berkovitz et al 1982) is a dense connective tissue (50% dry weight is collagen types I and III) between 0.15 and 0.3 mm wide. It contains cells typical of connective tissue with the addition of a network of epithelial cells, the *epithelial debris of Malassez*, remnants of the root sheath. These have no evident function but may produce commonly occurring *dental cysts*.

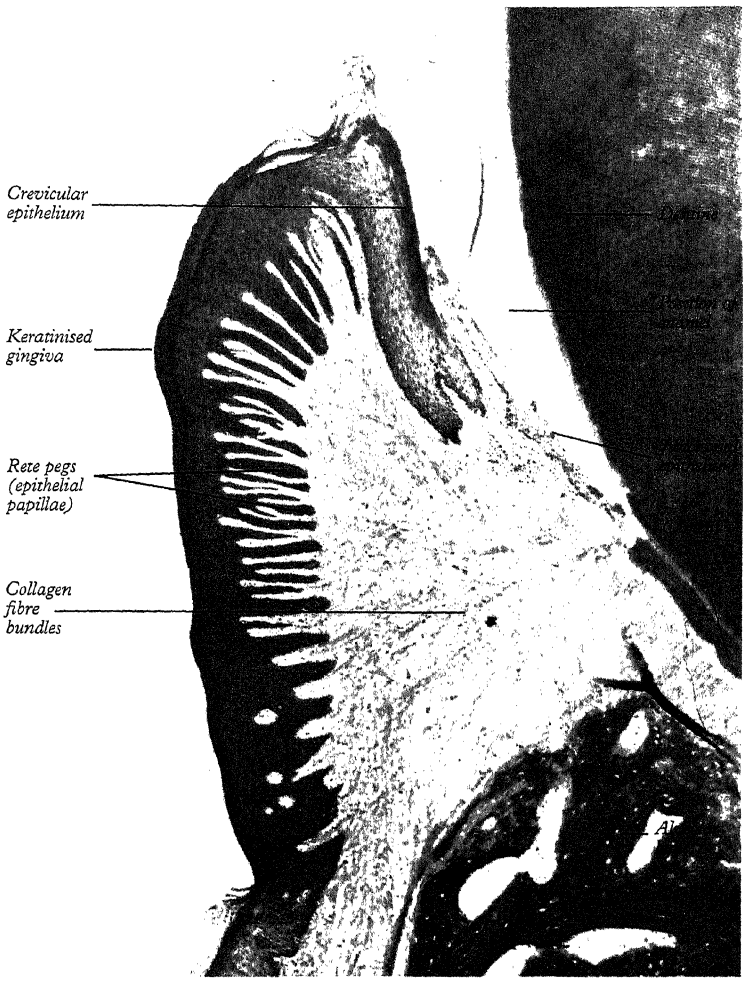
The principal functions of the periodontal ligament are to anchor the teeth in their sockets and to provide sensory information about tooth movements (Anderson et al 1970). The majority of collagen fibres are arranged in a number of *principal groups* which connect alveolar bone and cement. *Horizontal fibres* at the alveolar crest and near the apex restrict tilt; between these groups are the *oblique fibres*, restricting intrusive movement. Radiating from the apex are *apical fibres*, resisting extrusive movement. *Gingival fibres* pass from the cervical region of the root and from the osseous alveolar crest into the gingival lamina propria, anchoring it firmly to the tooth, aided by a *circular group* arranged concentrically around the neck. The collagen fibres compartmentalize the proteoglycan-rich hydrophilic ground substance (Sloan 1978) which provides a compressive viscoelastic support (Melcher & Walker 1976). Hydrodynamic damping, as blood is squeezed through the numerous vascular channels in the socket wall, also contributes to the dissipation of impact loads during mastication (Picton 1990).

Each periodontal ligament has a nerve supply from several sources (see above); the chief role of the innervation seems to be proprioception. Various endings have been described: irregularly branched, knob-like, Meissner's corpuscle-like, Ruffini-like and spindle-shaped. Structural variations of the mechanoreceptors appear to be less important than their spatial arrangement in determining the response (Hannam 1976; Linden 1990). Impulses from such endings probably provide an input to many brainstem centres and the cerebellum, where masticatory cycles may, in part, be integrated.

Turnover of collagen in periodontal ligaments is remarkably rapid. Fibroblasts are involved in both fibre synthesis and degradation, processes which may occur simultaneously within the same individual cell (Ten Cate & Deporter 1975).

GINGIVAE (GUMS)

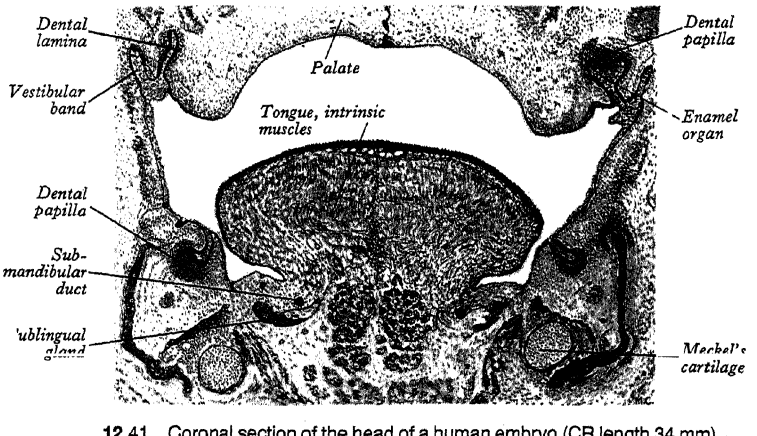
The gingiva is a specialized region of the oral mucosa surrounding the necks of the teeth (Squier et al 1976). In a healthy mouth it is distinguished from the oral mucosa by its pale pink, stippled appearance (**12.21, 40**), the adjacent alveolar mucosa being red, shiny and



12.40 Vertical demineralized section through the neck of a tooth and related gingiva (non-human primate). The enamel has been removed by the decalcification process, as indicated. In life, the junctional epithelium is adherent to the surface of the enamel. Magnification × 30.

smooth; gingival, palatal and dorsal lingual epithelia are keratinized (or parakeratinized), while alveolar epithelium is non-keratinized. Gingival lamina propria is firmly connected to the underlying alveolar bone, forming a virtually immovable mucoperiosteum.

At the gingival crest, the epithelium is reflected towards the root so that its outer surface is attached to the tooth, forming the *epithelial attachment*. Surrounding the tooth there may be a shallow *gingival sulcus* between tooth and gingiva, its floor being the epithelial attachment. The epithelium attached to the tooth is termed the *junctional epithelium*, that lining the sulcus is the *sulcular epithelium*. Junctional epithelium is non-keratinized, has wide intercellular spaces, few cytokeratin filaments and few desmosomes (Schroeder & Listgarten 1971); it is permeable, weakly cohesive and easily ruptured. Its superficial cells (equivalent to the prickle cells of normal keratinized epithelium) adhere tightly by hemidesmosomes to an outer basal lamina covering the adjoining dental surface (Listgarten 1970) to which they are firmly bonded; this is enamel in newly erupted teeth but in older individuals the junctional epithelium extends onto the cement. Junctional epithelial cells have a very high turnover and move rapidly up the dental surface, whence they are shed into the sulcus.



12.41 Coronal section of the head of a human embryo (CR length 34 mm), showing developing teeth. The pointer line to Meckel's cartilage passes through the developing mandible.

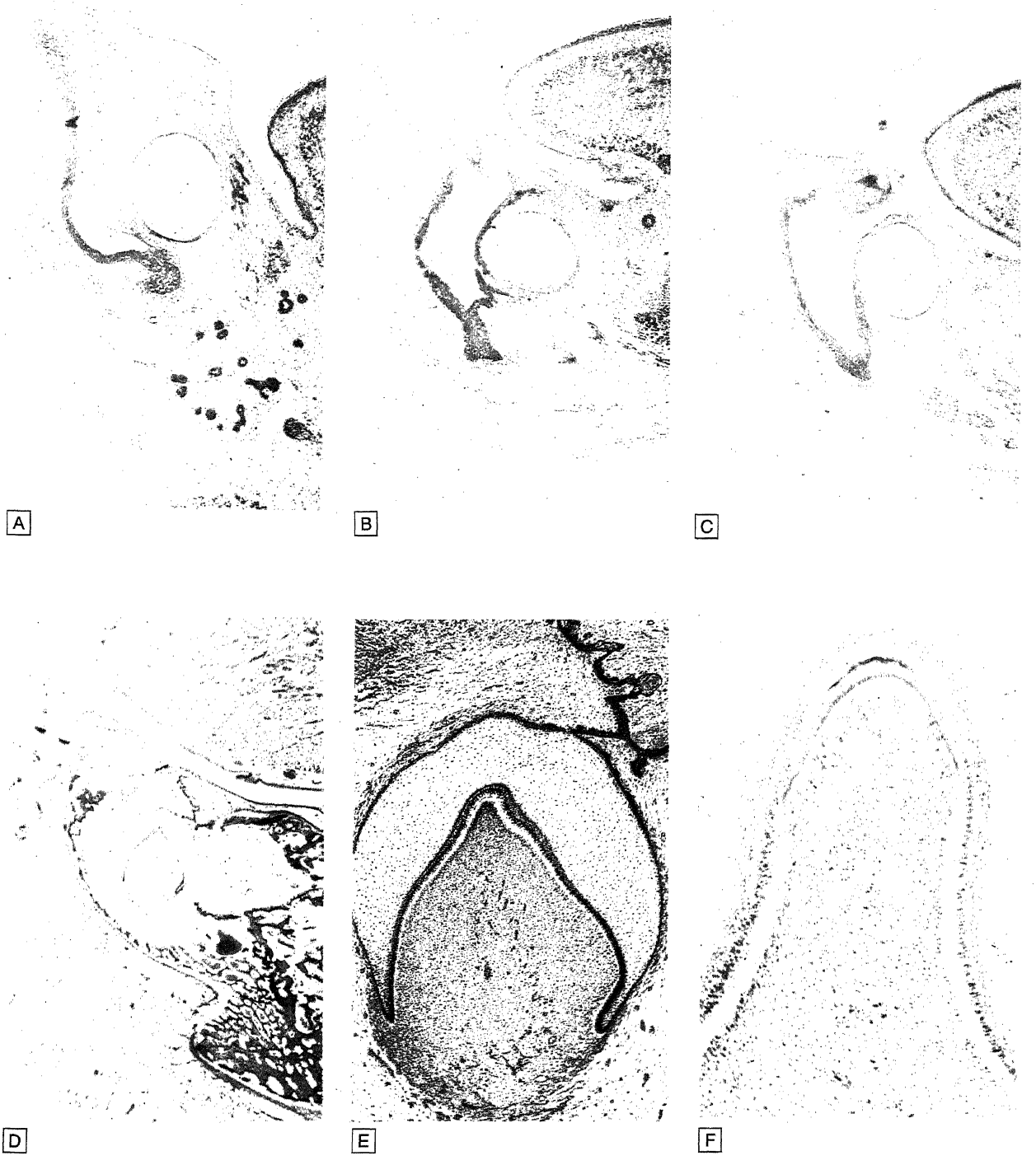
DECIDUOUS TEETH (12.41–48)

At the 9 mm embryonic stage primitive oral epithelium (**12.42A**) begins to bulge into the underlying mesenchyme where teeth will form (**12.41, 45**). From these separate ingrowths and the mesenchyme associated with them, the four anterior deciduous teeth (central and lateral incisors, canine and first molar) will arise (Ooé 1957; Nery et al 1970). In amphibian embryos, odontogenic mesenchyme originates from the mesencephalic levels of the cranial neural crests, migratory ectomesenchyme entering and expanding the branchial arches (de Beer 1947; Chibon 1967) under the inductive influence of oral epithelium (Wagner 1955; Henzen 1957). The tooth inductive potency of mandibular arch ectoderm on cranial neural crest cells has been demonstrated in the mouse embryo (Lumsden 1987).

At about the 20 mm stage the ingrown epithelial dental laminae have expanded into knob-like swellings (Ooé 1956), each surrounded by a dense aggregate of vascular mesenchyme (Gaunt 1959). The combined organ rudiment is the *tooth bud*. Ectoderm starts to grow around the mesenchymal aggregate; the ectodermal part is now an *enamel organ*, the mesenchymal part a *dental papilla*. Peripheral cuboidal cells of the enamel organ are soon distinguished from central polygonal cells. At this stage (48 mm) the bud of the second deciduous molar appears on the posteriorly growing dental lamina.

The spherical dental papilla enlarges but the encircling edge of the enamel organ (the *cervical loop*) continues to surround more of its periphery until it sits on the papilla like a cap, the *cap stage* of development (**12.42C**). Meanwhile the central polygonal cells of the enamel organ have been secreting glycosaminoglycans into intercellular spaces which attract water, swelling the enamel organ and compressing the cells. Since desmosomal connections persist, the central cells become stellar, forming a *stellate reticulum* (**12.42E, 43**). The originally cuboidal cells adjacent to the dental papilla lengthen to form the columnar cells of the *inner enamel epithelium* (**12.42E, 43**). Cells forming the outer surface of the enamel organ are the *outer (external) enamel epithelium* (**12.42E, 43, 45**), continuous via the dental lamina with the oral epithelium. By continued growth the cervical loop surrounds about three-quarters of the enlarging dental papilla, the *bell stage* of tooth development. Now a layer of flatter cells develops between the inner enamel epithelium and the stellate reticulum; this *stratum intermedium* derives from the original polygonal cells of the enamel organ (the *enamel knot*). Tissue interactions between the peripheral cells of the dental papilla and the adjacent cells of the inner enamel epithelium (Thesleff et al 1989) result in the differentiation of odontoblasts from the former and of ameloblasts from the latter.

The development of a nerve supply to deciduous teeth has attracted little attention. Alveolar nerves enter into maxillary and mandibular processes during the fifth week, before the dental laminae form (Pearson 1977). A close association has been noted between peripheral nerve branches and the sites of prospective tooth development in the mouse (Kollar & Lumsden 1979) but initiation of tooth development does not appear to depend on innervation (Lumsden & Buchanan 1986). At cap and bell stages bundles of nerve fibres have entered the dense mesenchyme of dental papillae and follicles.



12.42A–F A series of stages illustrating the early development of teeth. These are all coronal sections through the right half of the body of the mandible, showing the tongue in the top right-hand corner. The mandible is mineralizing to the left of the circular profile of Meckel's cartilage.

A. The stage of development before the ingrowth of the dental lamina from the oral epithelium.

B. The dental lamina is growing between the buccal and lingual plates of the ossifying mandible.

C. The cap stage of development. The enamel organ is growing from the dental lamina around the condensation of cells which forms the dental papilla.
Slightly later stages in tooth development than shown in **12.42A–C**.

D. The bell stage of development. The external enamel epithelium of the enamel organ is connected to the oral mucosa by an irregularly-stranded dental lamina. Lateral to the buccal plate of the mandible the vestibular band has atrophied centrally to initiate the oral vestibule. The tooth germ is separated from the bone by the tooth follicle.

E. A photograph at higher magnification of the bell stage. Note from above downwards: (1) the degenerating dental lamina, top right; (2) the fibrous tooth follicle surrounding the developing tooth; (3) the external enamel epithelium; (4) the delicate stippled appearance produced by the nuclei of the stellate reticulum; (5) the darkly stained, somewhat flattened cells of the stratum intermedium, which is seen more clearly in F; (6) the columnar cells of the internal enamel epithelium; (7) the more closely packed cells of the dental papilla which extend outside the cervical loop; (8) the capillaries of the pulp and tooth follicle.

F. Dentine formation beginning at the cuspal tip. From above downwards note: (1) the loose stellate reticulum; (2) the stratum intermedium; (3) a layer of columnar ameloblasts; (4) a thin strip of enamel matrix (mauve); (5) mineralized dentine (pink); (6) predentine (pale blue); (7) a layer of odontoblasts.

Dental follicle

This is the layer of cells which surrounds the tooth germ ultimately to adjoin developing alveolar bone (12.42D, 42E, 43, 45); the bony cavity containing the tooth germ and follicle is the *dental crypt*. The follicle cells adjacent to the outer enamel epithelium form a dense *investing layer* from which develops the cement of the root. The periodontal ligament and bone develop respectively from the loose intermediate layer and outer osteogenic layer of the follicle.

Vestibular band

As the dental laminae appear, a similar but continuous horseshoe-shaped ingrowth of epithelium develops external (buccal) to them. This *vestibular band (vestibular lamina)* (12.41, 44) grows deeply into the mesenchyme of the primitive jaws, separating prospective lips and cheeks from the tooth-forming regions. It subsequently thickens and cleaves at the *vestibular groove* (12.44) to form the *oral vestibule*. In contrast to the dental lamina, the vestibular lamina is not associated with an aggregation of mesenchyme cells.

PERMANENT TEETH (12.39, 46, 47)

As the jaws lengthen the dental lamina grows posteriorly from the distal aspect of the second deciduous molar germ as a solid cord of epithelium, not connected with the surface. From the deep border of this 'burrowing' lamina, buds for the three permanent molars develop in mesiodistal sequence, the first molar bud appearing in the 16-week fetus, the second at about 1 year and the third at 5 years. Each bud is initiated in the ramus of the lower jaw but, with progressive resorption of the anterior border of the coronoid process, they come to occupy the body of the mandible.

From each deciduous tooth germ at its bell stage (about 16 weeks) a lingual *successional lamina* grows from the site of continuity between outer enamel epithelium and dental lamina. Each grows down into mesenchyme lingual to a deciduous tooth and from its end a bud develops for a permanent successor which becomes surrounded by its own follicle and crypt. The follicle maintains fibrous continuity with the lamina propria of oral mucosa by *gubernacular cords*, whose original positions are visible in young skulls as *gubernacular canals*. The gubernacular canals are said to guide erupting permanent teeth into their correct positions (Scott 1967).

The fate of the dental laminae

As dentine and enamel start to develop, the dental laminae begin to degenerate (12.42E), separating into clumps, many with a whorled appearance over developing deciduous teeth. These persist as epithelial rests but may sometimes proliferate to form cystic cavities, known as *eruption cysts*, recognizable as bluish swellings over erupting teeth.

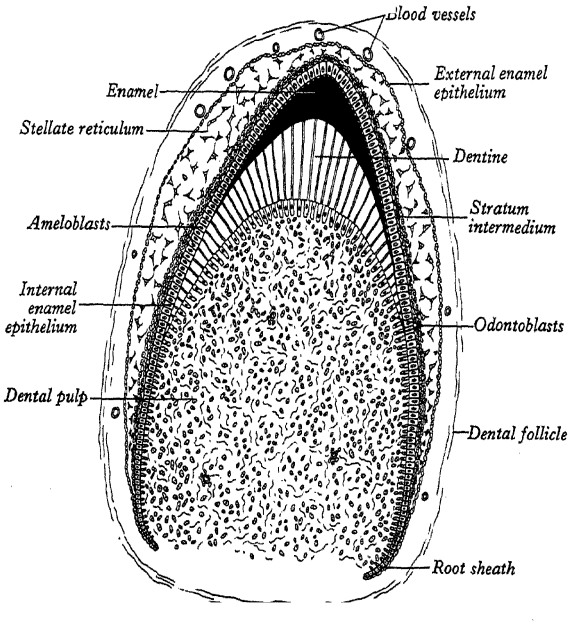
Crown pattern morphogenesis

During the late bell stage the amelodentinal membrane, formed by the inner enamel epithelium, the peripheral cell layer of the dental papilla and the interposed basement membrane, folds in a genetically determined pattern to assume the definitive outline of the future enamel–dentine junction. Because regional variations in enamel thickness are slight, this folding determines the ultimate shape of a tooth, i.e. the number and positions of cusps. Cap stage incisor and molar tooth germs of mouse embryos separated into their epithelial and mesenchymal components and reciprocally recombined in organ culture develop the morphology expected of the mesenchyme (Kollar 1972). How the dental papilla mesenchyme acquires positional specification and how the information for shape is encoded and relayed to the apparently indifferent enamel epithelium are unknown. For a further account of tooth development consult Ten Cate (1996).

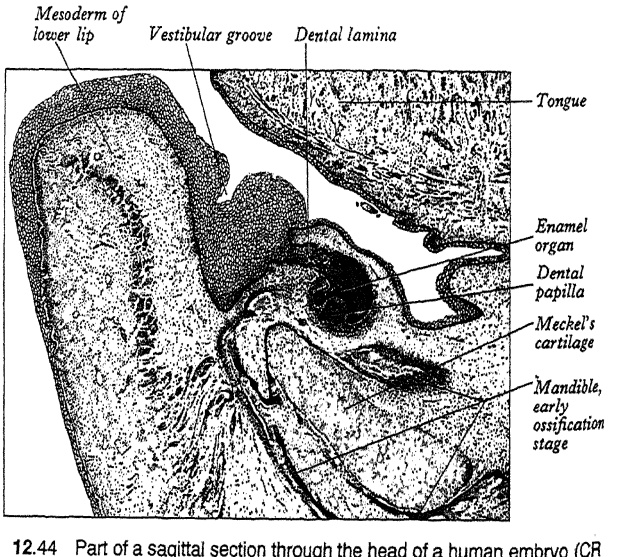
DEVELOPMENT OF DENTINE

At the tip of a presumptive cusp, cells of the inner enamel epithelium lengthen and mesenchyme cells of the adjacent dental papilla extend fine processes through the reticular lamina of the basement membrane to contact the epithelial basal lamina. An extracellular matrix-mediated cell to cell interaction (Thesleff 1977) induces the mesenchyme cells to differentiate into odontoblasts, which will lay down dentine (12.42F, 46, 47). Newly differentiated odontoblasts, with well-developed endoplasmic reticulum and Golgi apparatus, secrete dentine matrix into the space between the basal ends of the inner enamel cells and their own secreting ends. Collagenase-containing vesicles in this early matrix (Sorgente et al 1977) may be involved in digestion of the epithelial basal lamina which permits the odontoblast processes to push up between the inner enamel epithelial cells where they may form direct cell contacts, mediating the differentiation of ameloblasts. Accumulating matrix pushes the odontoblasts back, their processes lengthening as their perikarya recede, becoming enclosed within tubules of the matrix. As soon as a few microns of matrix are formed, the matrix adjacent to the inner enamel epithelium begins to mineralize (Silva & Kailis 1972), possibly with the agency of alkaline phosphatase-rich matrix vesicles (Bernard 1972, see also p. 472).

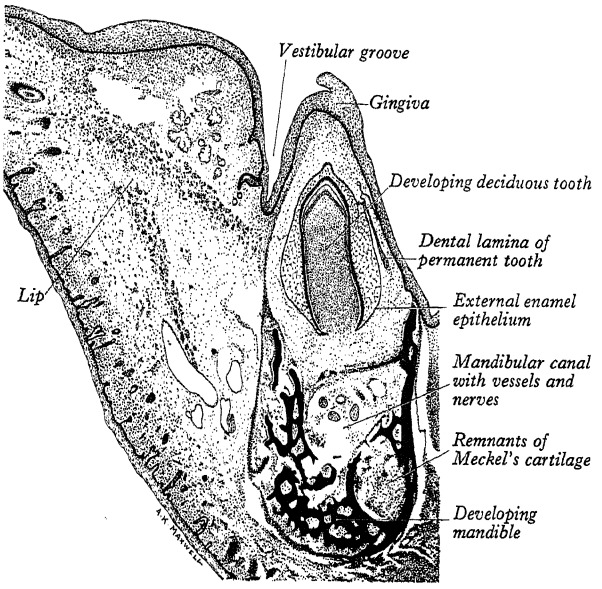
From this region, the summit of a presumptive dentine cusp, a wave of differentiation of odontoblasts from papillary cells slowly spreads to the growing cervical loop. As soon as each differentiates, the matrix is formed, pushing the layer of odontoblasts, united by desmosomes, into the papilla. The layer of unmineralized matrix



12.43 Simplified diagram of a developing tooth to show the approximate arrangement of its principal components. Compare with 12.42F.

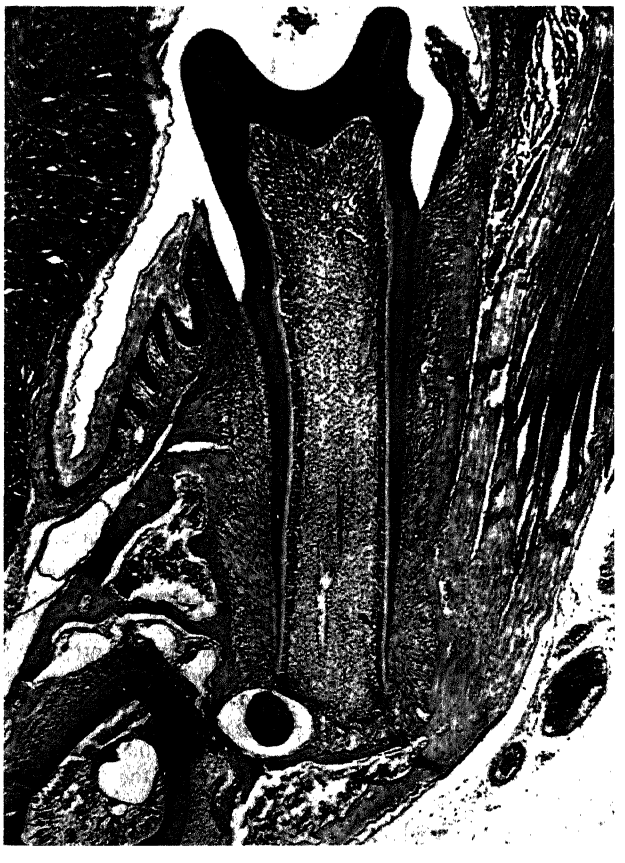


12.44 Part of a sagittal section through the head of a human embryo (CR length 60 mm), passing through the right lower central incisor tooth germ. Magnification ×12. (Drawn from a photomicrograph given by C H Tonge, Department of Oral Biology, University of Newcastle-upon-Tyne. Stained with haematoxylin and eosin.)

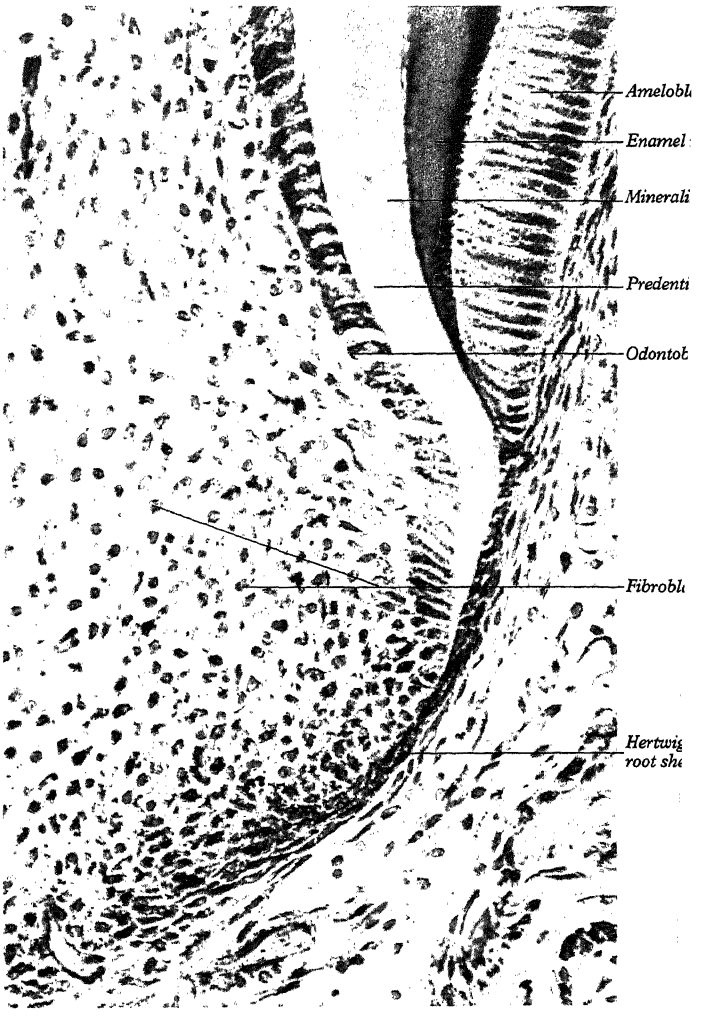


12.45 Developing tooth with mandible and lip in situ. (Drawn from a photograph by F Harrison, Dental Department, University of Sheffield, and reproduced from Pedley & Harrison with permission from Blackie.)

adjacent to the odontoblasts is termed predentine (**12.47**). First-formed collagen fibres lie parallel to the odontoblast processes; after this thin layer of *mantle dentine* (see above) is formed, fine collagen fibres of *circumpulpal dentine* are elaborated, interlacing at right angles to the processes. In mantle dentine each odontoblast has two or more processes but, as it recedes from the enamel–dentine junction, its processes unite into a single main process. This accounts for the bifurcation of the tubules near the junction. During circumpulpal dentinogenesis odontoblasts constantly extend short lateral processes at the base of the main process; these are later embedded by



12.46 A longitudinally sectioned developing tooth showing advanced root formation. See text for further details.



12.47 Vertical section through the neck of a developing tooth, with part of the crown above, and the developing root below. The layer of columnar ameloblasts terminate at the tooth neck where the latter is continuous with the developing root. Magnification x 600.

mineralized dentine to become fine lateral tubules. Dentinal tubules are much thinner in mineralized dentine than in predentine; this constriction starts at the level where predentine mineralization is beginning and is due to the deposition of a highly mineralized cylinder of *peritubular dentine* around the inside of the tubule, progressively reducing its lumen. It does not develop in interglobular areas (see above) where the tubule is walled by unmineralized intertubular dentine matrix.

DEVELOPMENT OF ENAMEL

Ameloblasts differentiate from cells of the inner enamel epithelium under the inductive influence of newly differentiated odontoblasts; the interaction between these cells is thought to involve direct cell contacts and/or the extracellular matrix. The first signs of differentiation are the manufacture of organelles required for enamel matrix production and the reversal of cell polarity; ameloblasts secrete from their original basal ends. Mitochondria, originally dispersed throughout the cytoplasm, congregate at the non-secreting pole where they cluster around the nucleus. The Golgi apparatus is located centrally; cisternae of the extensive endoplasmic reticulum are stacked in rows parallel to the cell's long axis. The mature cell is about 40 μm long and about 5 μm wide. In cross-section ameloblasts are regular hexagons, accounting for the classic honeycomb appearance, and are interconnected by junctional complexes at both secreting and non-secreting poles. Their non-secreting poles are attached by desmosomes to the stratum intermedium cells, which may

elaborate and transport materials to the ameloblasts (Kurahashi & Yoshiki 1972). Alkaline phosphatase, found in other hard-tissue forming cells, exists in the stratum intermedium but not in secretory ameloblasts.

Enamel matrix is secreted between mineralizing dentine and ameloblasts; a rise or potential rise in hydrostatic pressure produced by the accumulation of enamel matrix in this enclosed region probably provides the force to push ameloblasts away from the enamel–dentine junction (Osborn 1973). Since ameloblast differentiation depends on and shortly follows odontoblast differentiation, developing enamel spreads down the sides of the presumptive enamel–dentine junction in the same way as developing dentine, just behind it (**12**.47).

At the start of amelogenesis, in each region of the tooth germ, adjacent stellate reticulum seems to collapse, the enamel organ being progressively reduced in thickness until it has only three layers (outer enamel epithelium, stratum intermedium and ameloblast layer). It is widely assumed that this brings the ameloblasts, inside an avascular enamel organ, closer to the capillaries which have invaded the investing layer of the follicle adjacent to the external enamel epithelium. Meanwhile, cells of the latter, originally cuboidal, become squamous, throwing the outer surface of the enamel organ into microscopic folds to increase the area for diffusion.

When ameloblasts have moved about 10 μm from the enamel–dentine junction they develop conical extensions into the accumulating enamel. These *Tomes' processes*, whose bases are limited by the junctional complex at the secreting pole of the cell, bear a peripheral collar of microvilli (see Reith 1970). Tomes' processes give the developing front of enamel a pitted appearance (Boyde 1969); adjacent to each is an unmineralized layer about 50–100 nm thick, the *enamel matrix*. This is stippled under the electron microscope and similar material is seen in membrane-bound vesicles within Tomes' processes. On the enamel side of this stippled material are long ribbon-like crystallites. First-formed enamel is non-prismatic or contains irregular prisms. At the enamel–dentine junction, enamel (recognized by long crystallites) is intermixed with dentine (recognized by collagen fibres and small crystallites).

The mineralizing enamel front shows little change until nearly the full thickness of enamel has been secreted. This is immature enamel, containing narrow crystallites about 3 nm × 29 nm in cross-section, and has a composition of about 40% mineral by weight. As ameloblasts approach the final surface, deeper crystallites thicken by accretion of ions from the surrounding matrix. Diminishing calcium-rich matrix is replenished by ameloblasts, water and protein being resorbed. The matrix can travel long distances through the developing enamel. Ultimately the crystallites can widen no more, no further space being available between them. Theoretical analysis suggests that about 12% by volume of unmineralized enamel matrix and water would thus remain (Carlström 1964), according well with the observation that mature enamel is 96% by weight mineral (i.e. 88% by volume). No new crystallites appear to be added to the enamel except at the mineralizing front (Ronnholm 1962); crystals therefore grow in length as the enamel is deposited and achieve their final length as maturation begins. As secretion ends the ameloblast shortens, withdraws its previously conical Tomes' process and forms a ruffled membrane with numerous microvilli which endocytose the matrix (Reith 1967a,b). The maturative ameloblast contains numerous lysosomes. Over some of the enamel surface developed at this time, crystallites are parallel and prism sheaths are not formed (see above). This non-prismatic surface layer is about 6–12 μm deep (Gwinnett 1967; Osborn 1973) and is about 1% by weight more mineralized than the rest, possibly because of closer packing of crystallites by parallel orientation.

ROOT DEVELOPMENT

As enamel maturation proceeds towards completion of the tooth crown, the cervical loop of the enamel organ starts to recede from the cervical margin as a double-layered cylinder, Hertwig's root sheath, around the lengthening dental papilla. The outer layer of this sheath is continuous with the outer enamel epithelium (**12**.46, 47). The inner layer, like the inner enamel epithelium with which it is continuous, induces the differentiation of odontoblasts from contiguous mesenchyme cells. Odontoblasts now deposit a layer of dentine against the basal surface of the epithelium (**12**.46, 47). The sheath continues to grow, outlining the final shape of the roots and inducing differentiation of odontoblasts, surrounding vessels and nerves supplying the dental papilla. These vessels remain and it is because of them, particularly those located centrally near the future apex, that the foramina open through canals in the dentine into the pulp of a fully developed tooth.

During crown development the capillaries are most numerous beneath the cuspal growth centres. The papilla grows more rapidly near the capillaries, and less rapidly elsewhere. In the latter regions a growing tip of root sheath is able to penetrate under the papilla to meet a growing tip from the other side, separating the two roots. They may, however, just fail to meet, in which case a single flattened root is formed with two root canals. Thus the principal cusps of a multicusped tooth are each supported by a root, which is either separate or incompletely separated from its neighbours.

DEVELOPMENT OF CEMENT

Shortly after initial dentinogenesis in the root, the adjacent root sheath epithelium becomes fenestrated (see below), exposing the unmineralized exterior of the dentine to the vascularized follicular mesenchyme, from whose investing layer cementoblasts are differentiated. These early cementoblasts do not synthesize collagen but secrete ground substance onto the dentine matrix and around bundles of collagen fibres developed in the follicle which have fanned out on the dentine surface. This composite matrix (which may also include epithelial cell secretions, see above) is mineralized under the influence of cementoblasts (Owens 1975). The collagen fibre bundles are about 6 μm wide and their cores mineralize more rapidly than their peripheries. Because it is unmineralized at the time of its formation, the junction between dentine and cement has crystalline continuity and is hence not easy to define in electron micrographs.

First-formed cement, containing only extrinsic collagen fibres, develops while the tooth is erupting and is therefore present on the cervical third of the root dentine. Cementoblasts differentiate over the remainder of the root and, in all later cement, contribute collagen fibres to the matrix (Jones & Boyde 1972). This mixed fibre cement therefore contains both *extrinsic* (Sharpey's) *fibres* of periodontal origin and *intrinsic fibres* from cementoblasts, the former being perpendicular to the developing surface, the latter parallel. Intrinsic fibres are mineralized first. Sharpey's fibres are then mineralized around their peripheries, while the cores are unmineralized. In later or more rapid cementogenesis, the cementoblasts are frequently trapped within the matrix; cellular cement is most commonly formed around the apical two-thirds of the root surface.

DEVELOPMENT OF THE PERIODONTIUM

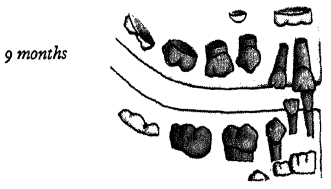
During the cap and bell stages of tooth development some cells of the dental papilla are displaced by the growing cervical loop to lie adjoining the outer enamel epithelium. Cementoblasts and fibroblasts of the tooth-related periodontal ligament are probably derived from these cells (Ten Cate 1975; Palmer & Lumsden 1987). It has even been suggested that they give rise to osteoblasts of the alveolar bone, but this remains to be definitely demonstrated (Lubbock 1993).

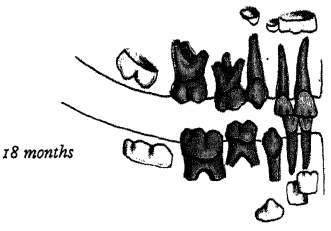
The principal oblique fibre group of the ligament becomes organized at the time of root development and eruption, with an orientation which is visible first as an oblique array of fibroblasts. Once formed, their oblique orientation is maintained as the tooth moves relative to the alveolar bone. Based on its appearance in sections, it was formerly considered that the principal fibres were formed, broken and reformed at an intermediate plexus in the central zone of the ligament (Hindle 1967). However, autoradiographic studies following tritiated proline uptake have not confirmed that collagen turnover is faster in the central zone than elsewhere (Rippin 1976).

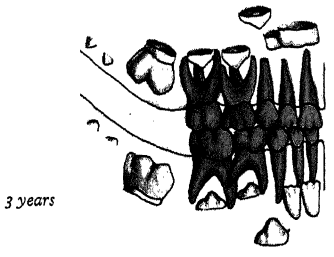
The epithelial debris of Malassez is formed by the remains of Hertwig's root sheath which, following its fenestration and the translocation of presumptive cementoblasts from the follicle to the dentine surface, moves away from cement into the tooth-related periodontal ligament.

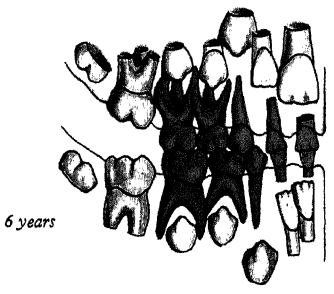
DENTAL ERUPTION

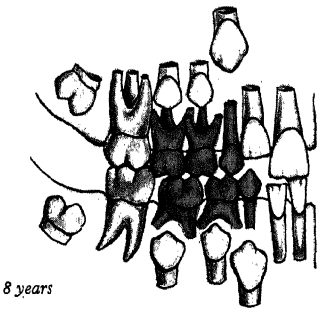
When the deciduous dentition is initiated, the five tooth germs in

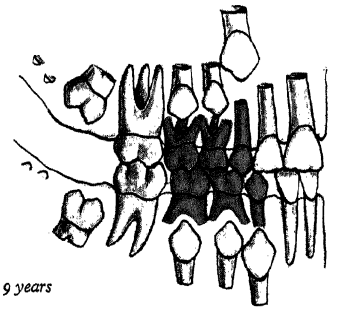


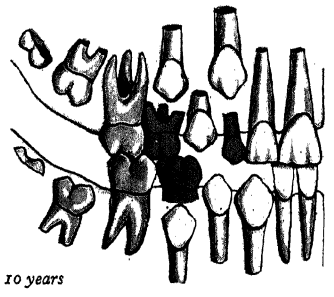


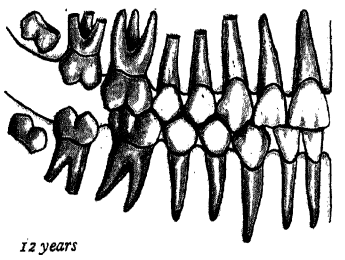


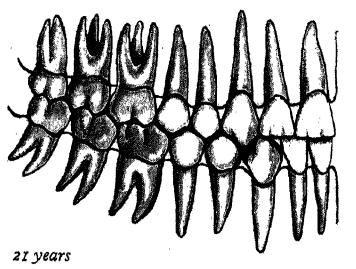




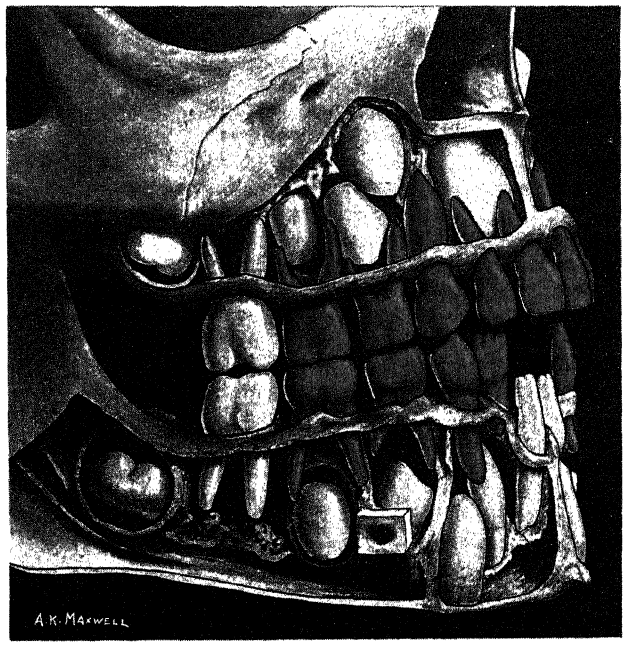








12.48 Development of the deciduous (blue) and permanent (yellow) dentitions from birth to maturity. Modified from Schour & Massler (1941).



12.49 Dentition of a child of seven years (deciduous teeth: blue, permanent teeth: yellow) showing a common variant in which the upper permanent lateral incisor is missing. The lower permanent central incisors have replaced the deciduous central incisors and the first permanent molars have erupted. (Drawn from a photograph by F Harrison, Dental Department, University of Sheffield and reproduced from Pedley & Harrison by permission of Blackie.)

each quadrant occupy jaws which are about 1 mm long. By the time the teeth have erupted into the oral cavity they occupy 3 or 4 cm of jaw; during development the teeth have migrated apart. It is not known how this movement is brought about.

Very soon after root formation starts, the teeth begin to move towards the oral cavity (Darling & Levers 1976). The origin of the forces which move teeth is not certainly known. A tooth could be **pushed** by growth of its root, proliferation of cells in the pulp or by tissue hydrostatic pressure. In support of the latter, the eruption rate can be experimentally altered by cervical sympathectomy or the administration of vasoactive drugs (Moxham 1979). But as Burn-Murdoch (1990) points out, such experiments do not prove that tissue fluid pressure is the cause of eruption because changes in blood flow could affect several possible eruptive mechanisms. Alternatively, a tooth could be **pulled** out of its socket by shrinkage of the obliquely placed collagen fibres (Thomas 1976) or by the movement of fibroblasts within the periodontal ligament (Beertsen et al 1974). It has also been suggested that the remodelling of alveolar bone may cause eruption (Marks & Cahill 1984). In reality, several of the above factors are likely to co-operate in the eruptive process (Moxham & Berkovitz 1983).

The permanent incisors and canines initially develop lingual to their predecessors (**12.48, 49**) but erupt along labially-inclined paths. This movement is associated with the intermittent but progressive osteoclastic resorption of the roots of deciduous teeth (Furseth 1968). In periods of quiescence, the resorbed tissues are temporarily repaired by the deposition of cement.

Early in its development, each premolar moves directly deep to its predecessor to become lodged between widely-divergent roots (**12.23, 49**). As the premolar erupts it induces resorption of the deciduous molar. The enamel of the underlying permanent tooth is protected from resorption by its *reduced enamel epithelium* (see p. 1715).

Eruption times of teeth

Information on the development of teeth and their emergence ('eruption') into the oral cavity is important in clinical practice and also in forensic medicine and archaeology. The tabulated data provided in Table **12.1** are largely based on European-derived populations (see also **12.48, 49**). The developmental stages of initial calcification and crown completion are less affected by environmental influences than eruption, the timing of which may be modified by several factors such as caries, tooth loss and severe malnutrition.

ALVEOLAR DEVELOPMENT

Jaws begin to develop when the dental lamina is forming. In the mandible the growing margin of membrane bone lateral to Meckel's cartilage passes back caudal to the inferior alveolar nerve; from it lateral and medial plates grow upwards (Dixon 1958). Developing teeth thus appear to descend between the plates (**12.45**). An osseous horizontal partition divides the teeth from the inferior alveolar nerve and vertical septa later isolate each tooth in its own crypt. Bone does not develop over deciduous teeth and in skeletonized neonatal jaws teeth are usually lost. A similar process is involved in the development of maxillary crypts.

When the teeth start to move towards the oral cavity, their sockets also grow, deepening the crypts and increasing the height of the jaw. The rate of eruption outstrips the rate of upward bone growth until the teeth meet their opponents. Developing roots have wide open apices but these later close around nerves and vessels to form foramina. The lengthening of osseous sockets for the teeth much increases the depth of the face up to and during puberty (Scott 1967).

CUTICLES AND EPITHELIAL ATTACHMENT

At the end of amelogenesis, the cells of the enamel organ revert to a squamous shape, becoming a thin stratified layer covering the whole surface of the enamel. This is referred to as the *reduced enamel epithelium*. During eruption it fuses with the oral epithelium to provide an epithelium-lined path for the tooth. The reduced enamel epithelium is rapidly worn away from the exposed surface of the tooth except at the neck where it forms the *epithelial attachment* (**12.41, 46**) at the dentogingival junction. The reduced enamel epi-

Table 12.1 Chronology of the human dentition

Dentition	Tooth	First evidence of calcification (weeks in utero for deciduous teeth)	Crown completed (months)	Eruption (months)	Root completed (years)
Deciduous upper	i1	14	1½	10 (8–12)	1½
	i2	16	2½	11 (9–13)	2
	C	17	9	19 (16–22)	3¼
	m1	15½	6	16 (13–19)	2½
	m2	19	11	29 (25–33)	3
Deciduous lower	i1	14	2½	8 (6–10)	1½
	i2	16	3	13 (10–16)	1½
	C	17	9	20 (17–23)	3¼
	m1	15½	5½	16 (14–18)	2¼
	m2	18	10	27 (23–31)	3
Permanent upper	I1	3–4 month	4–5 yr	7–8 yr	10
	I2	10–12 month	4–5 yr	8–9 yr	11
	C	4–5 month	6–7 yr	11–12 yr	13–15
	P1	1½–1¾ yr	5–6 yr	10–11 yr	12–13
	P2	2–2¼ yr	6–7 yr	10–12 yr	12–14
	M1	at birth	2½–3 yr	6–7 yr	9–10
	M2	2½–3 yr	7–8 yr	12–13 yr	14–16
	M3	7–9 yr	12–16 yr	17–21 yr	18–25
Permanent lower	I1	3–4 month	4–5 yr	6–7 yr	9
	I2	3–4 month	4–5 yr	7–8 yr	10
	C	4–5 month	6–7 yr	9–10 yr	12–14
	P1	1¾–2 yr	5–6 yr	10–12 yr	12–13
	P2	2¼–2½ yr	6–7 yr	11–12 yr	13–14
	M1	at birth	2½–3 yr	6–7 yr	9–10
	M2	2½–3 yr	7–8 yr	11–13 yr	14–15
	M3	8–10 yr	12–16 yr	17–21 yr	18–25

From Ash M M 1993 Dental anatomy, physiology and occlusion W B Saunders Co, Philadelphia (slightly modified).

thelium is separated from the enamel surface by a structureless layer, the *primary enamel cuticle*, about 1 μm thick, which may be the final, unmineralized product of ameloblasts. This cuticle together with the reduced enamel epithelium is called *Nasmyth's membrane*. A form of cement known as *afibrillar cement* has been observed over the enamel around the necks of teeth (Listgarten 1966). Afibrillar cement is only about 100 nm thick, contains no banded collagen and is probably produced by cementoblasts following premature disruption of part of the reduced enamel epithelium. Occasionally a cuticle about 4 μm thick is found between the epithelial attachment and the tooth. This is the *secondary enamel cuticle*. It may be a product of the epithelial cells or it may be the remains of blood which has leaked through the epithelial attachment following some slight trauma (Hodson 1966). Finally, salivary protein and carbohydrate form an adherent film on tooth surfaces. This is known as the *pellicle* and is the foundation of *dental plaque*.

CLINICAL ASPECTS

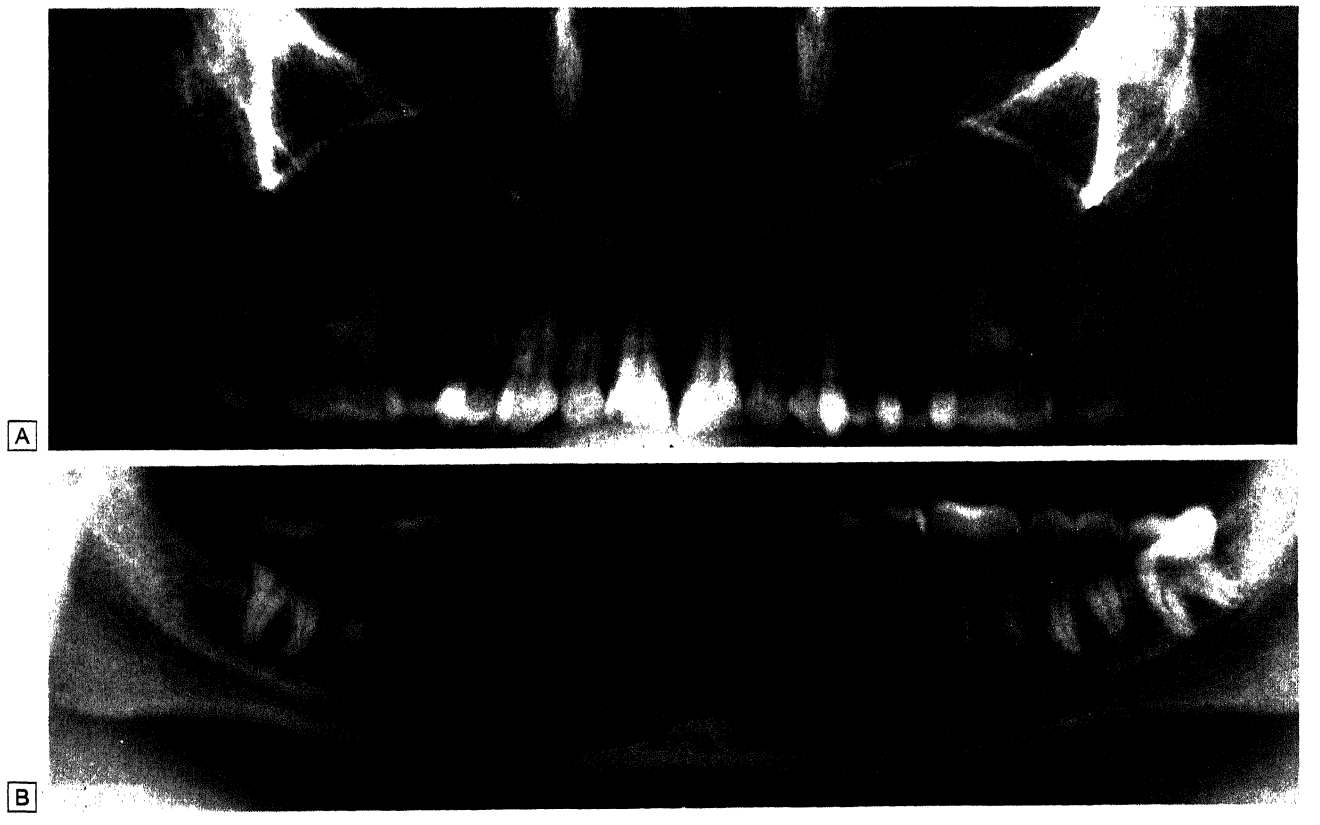
The cortical plate of bone in each jaw is continuous over the alveolar crest with the cortical plate lining the tooth socket (the *cribriform plate* or *lamina dura* of radiographs). On the labial and buccal aspects of *upper teeth*, these two cortical plates usually fuse with very little trabecular bone between them, except where the buccal bone thickens over the molar teeth near the root of the zygomatic arch (DuBrul 1988). It is easier and more convenient to extract upper teeth by fracturing the buccal than the palatal plate. Anteriorly in the *lower jaw*, labial and lingual plates are thin but in the molar region the buccal plate is thickened as the external oblique line. Near the lower third molar, the lingual bone is much thinner than the buccal and it is mechanically easier to remove this tooth, when impacted, via the lingual plate. However, the lingual nerve is here exposed to damage.

Abscesses developing in relation to the apices of roots ultimately penetrate the surrounding bone where it is thinnest. The position of the resultant swelling in the soft tissues is largely determined by the relationship between muscle attachments and the sinus (the path taken by the infected material) in the bone. Thus, in the lower incisor region, because the labial bone is thin, abscesses generally appear as a swelling in the labial sulcus, above the attachment of the mentalis. But the abscess may open below the mentalis and point beneath the chin. If an abscess from a lower postcanine tooth opens below the attachment of the buccinator, the swelling is in the neck; if it opens above, the swelling is in the buccal sulcus. If an abscess opens lingually above the mylohyoid, the swelling is in the lingual sulcus; if it is below, the swelling is in the neck. Because the mylohyoid ascends posteriorly, third molar abscesses tend to track into the neck rather than the mouth.

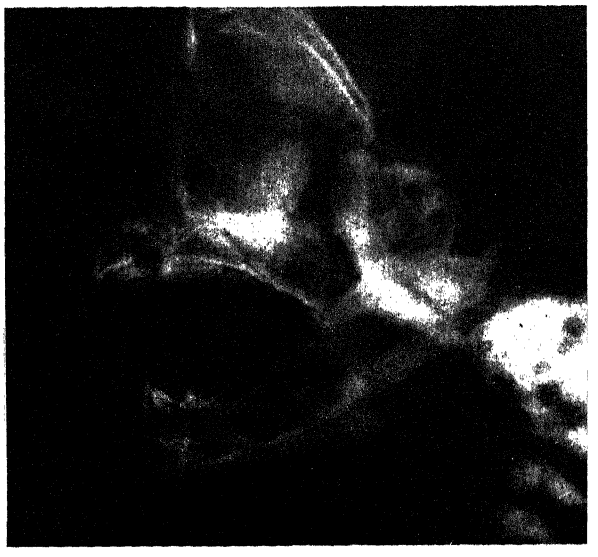
Apart from canine teeth, which have long roots, abscesses on upper teeth usually open buccally below, rather than above, the attachment of buccinator. Because its root apex is occasionally curved towards the palate, abscesses of the upper lateral incisors may track into the palatal submucosa. Abscesses of upper canines often open facially just below the orbit. Here the swelling may obstruct drainage in the angular part of the facial vein (p. 1577) which has no valves; it is therefore possible for infected material to travel via the angular and ophthalmic veins into the cavernous sinus. Abscesses on the palatal roots of upper molars usually open on the palate.

Upper second premolars and first and second molars are related to the maxillary sinus. When this is large, the root apices of these teeth may be separated from its cavity solely by the lining mucosa. Sinus infections may stimulate the nerves entering the teeth, simulating toothache. Upper first premolars and third molars may be closely related to the maxillary sinus.

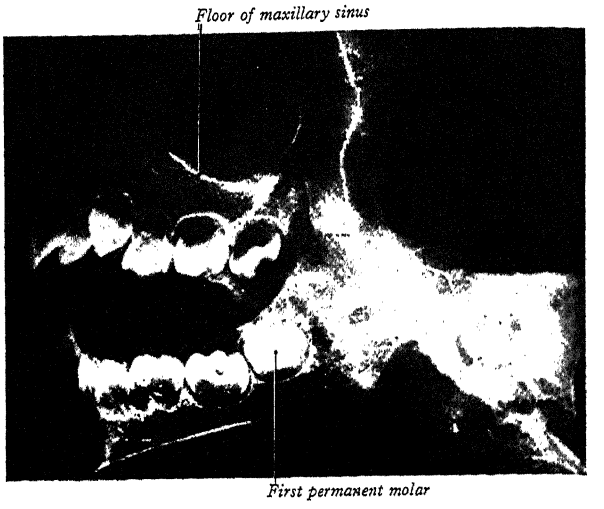
With loss of teeth, alveolar bone is extensively resorbed. Thus in the edentulous mandible the mental nerve, originally inferior to premolar roots, may lie near the crest of the bone. In the edentulous maxilla, its sinus may enlarge to approach the bone's oral surface.



12.50A, B Pan-oral radiographs of the whole dentition of A the upper and B lower jaws of a mature human skull. Note the right lower third molar is missing. To achieve these radiographs, an X-ray source is introduced into the buccal cavity, directed towards the palate for the upper jaw and towards the floor of the cavity for the lower jaw. The X-ray beam is deflected magnetically to disperse anterolaterally and the film is wrapped around the external aspect of the jaws. The clarity of the radiographs is much greater than that possible during clinical radiography of the living head. (The radiographs were prepared by D White of the X-ray Department of the Royal Dental Hospital, London.)



12.51 A lateral radiograph of the jaws of a newborn child. Note the state of development of the jaws and teeth.



12.52 Radiograph of the jaws of an infant, nine months old (from Symington & Rankin *Atlas of Skiagrams*). Only the lower central incisor has erupted; the roots of the first lower deciduous molar are just beginning to form; the crown of the first lower permanent molar faces inwards.

Lingual to the lower premolars or molars, the upper molars and in the midline of the palate, there are occasional bony prominences termed the *torus mandibularis*, *torus maxillaris* and *torus palatinus* (p. 563). They may need surgical removal before satisfactory dentures can be fitted.

Severe systemic infections during the time the teeth are developing may lead to faults in enamel, visible as horizontal lines (cf. Harris's growth lines p. 441).

FORENSIC APPLICATIONS

Dental evidence is valuable in three areas of forensic medicine:

- identification of individuals, especially following mass disasters
- estimation of age at death of skeletonized remains
- cases of criminal injury by biting.

If some teeth have been repaired, extracted or replaced by a denture, an individual will have a virtually unique dentition and the dentist will have recorded it in the form of charts, radiographs or plaster casts. Being the most indestructible bodily structures, teeth can provide an identification when trauma or fire has rendered the face unrecognizable. Estimating age may also of course help to establish a body's identity. The chronology of crown development, eruption and root formation can be used to estimate age until the third molar is completed at about 21 years. The method is even applicable to the fetus: Stack (1964) has shown that the weight of mineralized tissue in teeth is closely related to age from about 22 weeks' gestation until birth. Parturition is indicated in the deciduous dentition and first permanent molars by a neonatal line, identifiable in ground sections of teeth or by electron microscopy and which can serve as a marker in estimating the age of an infant by counting the subsequent incremental striae of Retzius formed at intervals of 7–8 days. Since structural changes occur throughout life in all dental tissues, teeth can be used to determine the age of an adult. The features used for this purpose include wear of the crown, reduction in size of the pulp and increase in thickness of cement in the apical half of the root. But the most useful single characteristic is the amount of sclerotic or translucent dentine in the root. This begins to form at the apex and progresses cervically, its linear extent as seen in longitudinally sectioned teeth being proportional to age. Such estimations are within 5–7 years of the chronological age (Whittaker 1992) and likely to be closer to the true age than those derived from skeletal changes.

Photographs of dermal bite marks can be compared with casts of a suspect's dentition: unusual irregularities in form or arrangement of teeth will aid in the culprit's identification. Saliva obtained from bite marks may be even more useful: in most people it contains blood group agglutinogens in very high concentrations. But saliva also contains cells and hence a precise biochemical identification by DNA 'fingerprinting' may be possible.

DENTAL RADIOLOGY

Due to dense mineralization, the enamel and dentine are radio-opaque whereas pulp appears as a radiolucent region (12.50, 51, 52, 53). Caries, which attacks teeth through the enamel or root surface, is easily diagnosed by intraoral radiographs because it demineralizes teeth. The root of a tooth is separated from cortical bone (*lamina dura*) by the radiolucent periodontal ligament. Chronic infections of the pulp spread into this ligament, leading to resorption of the

12.53 Radiograph of the teeth of a boy, aged five years (from Symington & Rankin *Atlas of Skiagrams*). In the maxilla the lateral deciduous incisor and the first deciduous molar have been lost, but all the deciduous teeth are present in the mandible. No absorption of the roots of the deciduous teeth has occurred. No permanent teeth have erupted.

lamina dura around the dental apex. Thus continuity of the lamina dura around the apex of a tooth usually indicates a healthy apical region, except in acute infections where resorption of bone has not yet begun.

Anteriorly, interdental septa form sharp crests between the teeth; between molariform teeth they form tables. In periodontal disease, the eventual sequel to gingival disease, bony crests or tables are resorbed and the extent of the condition can therefore be determined radiographically.

Radiographs are commonly used to estimate separation between the roots of maxillary teeth and the maxillary sinus; roots of the second premolar and first and second molar often project into the sinus. Mandibular third molars are commonly prevented from erupting by impaction against the second molars and radiographs are indispensable in assessing the degree of difficulty in extracting such teeth. Superior to the mental spines (genial tubercles), many mandibles exhibit a well-defined pit ending in a canal, presumably containing a median blood vessel or perhaps penetrating collagen fibres connected to the lingual frenulum. This pit, together with a radio-opaque ring of compact bone, can usually be seen in radiographs of incisors and is a useful median landmark in an edentulous mandible.

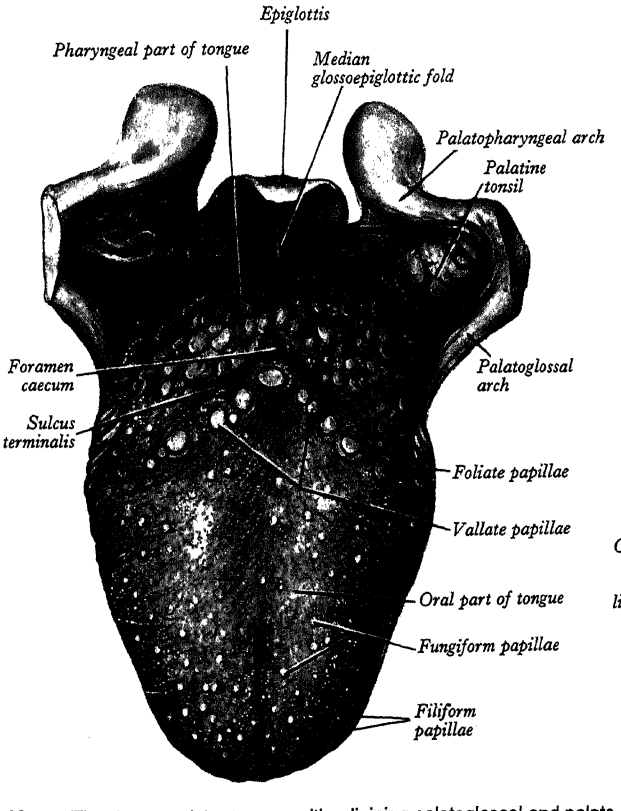
TONGUE AND PHARYNX

TONGUE

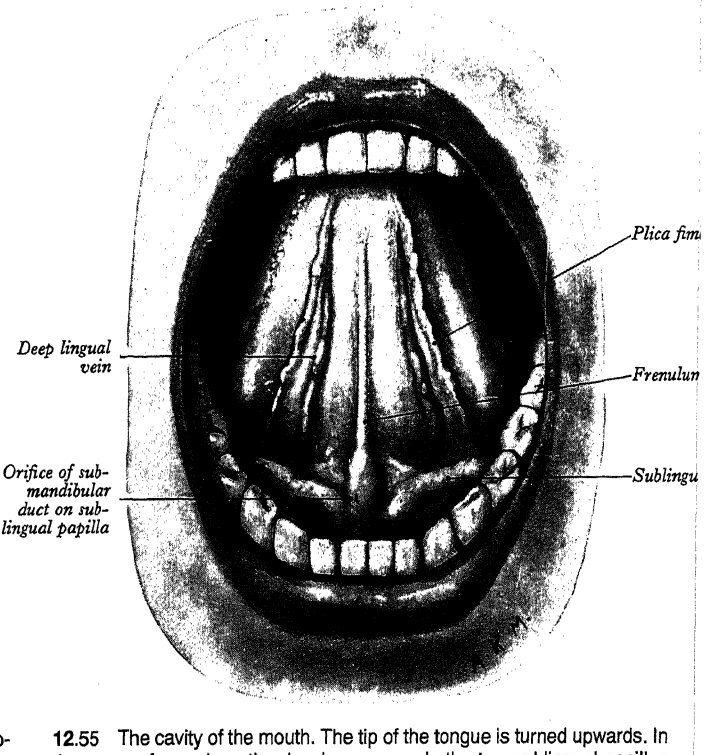
The tongue (**12.54, 55, 56**) is a highly muscular organ of deglutition, taste and speech. It is partly oral and partly pharyngeal in position, and is attached by its muscles to the hyoid bone, mandible, styloid processes, soft palate and the pharyngeal wall. It has a *root*, an *apex*, a curved *dorsum* and an *inferior surface*. Its mucosa is normally pink and moist, and is attached closely to the underlying muscles. The *root of the tongue* (**12.55**) is attached to the hyoid bone and mandible; between these it is in contact inferiorly with the geniohyoid and mylohyoid muscles. The *dorsum* (posterosuperior surface) is generally convex in all directions at rest. It is divided by the V-shaped *sulcus terminalis* into an *anterior, oral* or *presulcal part* facing upwards and a *posterior, pharyngeal* or *postsulcal part* facing posteriorly, the anterior part forming about two-thirds of the tongue's length. The two limbs of the sulcus terminalis run anterolaterally to the palatoglossal arches from a median depression, the *foramen caecum* (**12.54**), the site of the upper end of the embryonic thyroid diverticulum (p. 175). The oral and pharyngeal parts of the tongue differ in their mucosa, nerve supply and developmental origins (p. 1714).

Oral (presulcal) part (**12.54, 55**). Located in the floor of the oral cavity, this has an *apex* touching the incisor teeth; a *margin* in contact with the gums and teeth; and a *superior surface* (dorsum) related to the hard and soft palates. On each side, in front of the palatoglossal arch, are four or five vertical folds, the *foliate papillae* (**12.54**). The dorsal mucosa has a longitudinal *median sulcus* (**12.54**), and is papillated. The inferior mucosa is smooth, purplish and reflected on to the oral floor and gums, being connected to the former anteriorly by the median mucosal fold, the *frenulum linguae* (**12.55**); lateral to this on either side, the deep lingual vein is visible, and lateral to the vein is a fringed mucosal ridge, the *plica fimbriata*, directed anteromedially towards the lingual apex. The oral part of the tongue develops from the lingual swellings of the mandibular arch and from the tuberculum impar (p. 175). Its general sensory nerve is the lingual branch of the mandibular, whilst the chorda tympani branch of the facial mediates taste. (For the origin of lingual musculature see p. 274.)

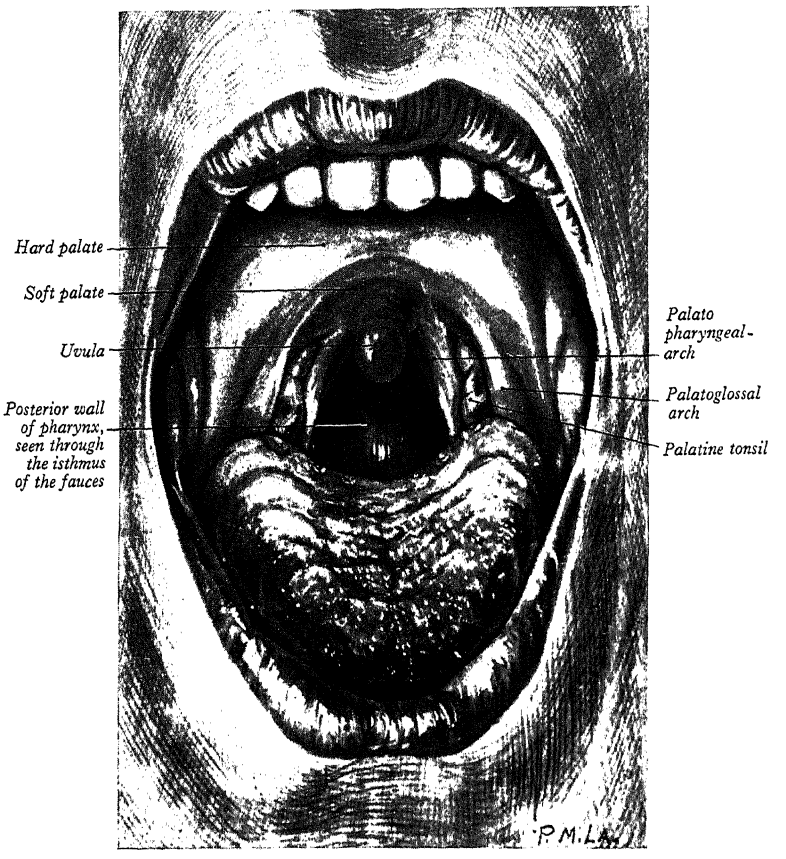
Pharyngeal (postsulcal) part (**12.54**). Forming the base of the tongue, it lies posterior to the palatoglossal arches within the oropharynx, forming its anterior wall. Its mucosa is reflected laterally on to the palatine tonsils and pharyngeal wall and posteriorly on to the epiglottic folds. Devoid of papillae, it has low elevations, due to lymphoid nodules embedded in the submucosa, collectively termed the *lingual tonsil*. The ducts of small seromucous glands open on the



12.54 The dorsum of the tongue, with adjoining palatoglossal and palatopharyngeal arches, and epiglottis. Note the palatine tonsils in the tonsillar recesses on either side.



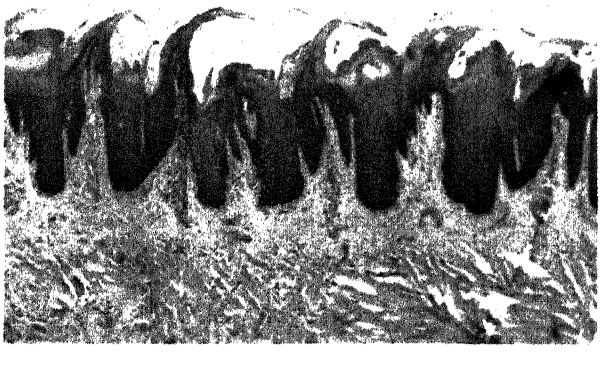
12.55 The cavity of the mouth. The tip of the tongue is turned upwards. In the person from whom the drawing was made the two sublingual papillae formed a single median elevation.



12.56 The cavity of the mouth with the tongue depressed, showing the oral cavity and also the oropharyngeal isthmus between the palatoglossal folds.

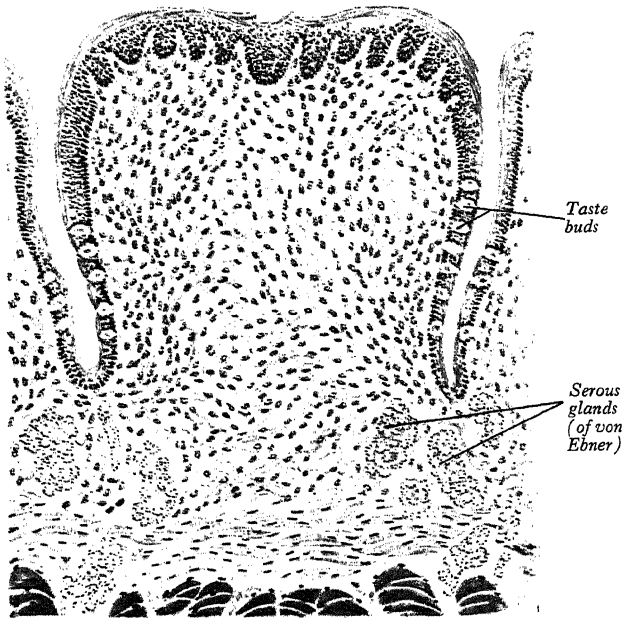
apices of these elevations. The postsulcal tongue develops from the hypobranchial eminence (p. 175). Its sensory nerve, including general sensation and taste, is the glossopharyngeal, whose rami also extend to a narrow strip of mucosa anterior to the sulcus terminalis to supply the taste buds of the vallate papillae, an arrangement explained by the embryonic extension of the hypobranchial eminence (derived from the third pharyngeal arch) anteriorly over the posterior part of the lingual swellings (p. 175). Rarely the thyroid gland fails to migrate away from the tongue during development, and then forms a lingual thyroid gland.

Lingual papillae (**12.54**). These are projections of mucosa from the dorsum of the tongue. (See also p. 1687.) They are numerous but limited to the presulcal part of the dorsum, producing its characteristic roughness; there are four principal types: *filiform*, *fungiform*, *foliate* and *vallate papillae*. All except the filiform papillae bear taste buds. These projections are modifications of mucous membrane which increase the area of contact between the tongue and the contents of the mouth, and in some cases are also gustatory structures. *Taste buds* (see p. 1312) are microscopic barrel-shaped epithelial structures which contain chemosensory cells in synaptic contact with the terminals of gustatory nerves; they are not restricted to the papillae, being scattered over the entire lingual dorsum and sides, epiglottis and lingual aspect of the soft palate. They are innervated by the appropriate gustatory nerves (facial, glossopharyngeal or vagal according to their position). The papillae are more visible in the living when the tongue is dry.

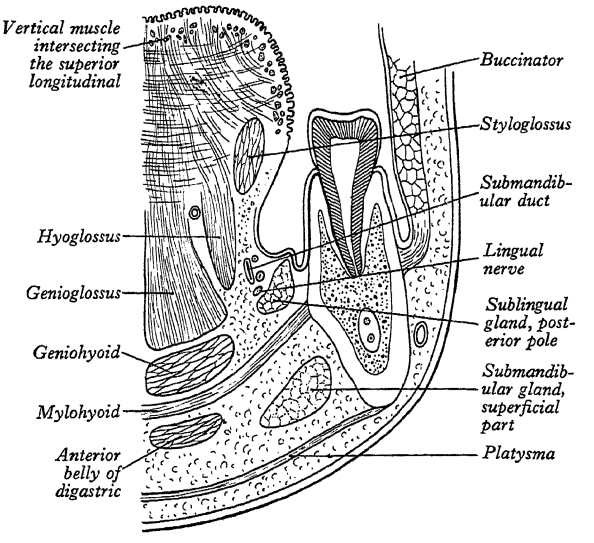


12.57 Section through filiform papillae from the anterior part of the tongue, showing keratinized stratified squamous epithelial covering and connective tissue papillae. Haematoxylin and eosin. Magnification × 300.

12.58 Vertical section through a fungiform papilla, stained with haematoxylin and eosin (primate). Magnification × 300.



12.59 Section through a vallate papilla (after Sobotta). Stained with haematoxylin and eosin. Magnification × 32.



12.60 Diagram of a coronal section through the tongue, the mouth and the body of the mandible opposite the first molar tooth.

Filiform papillae (12.57). Covering most of the presulcal dorsal area (Kullaa-Mikkonen et al 1987), they are minute, conical or cylindrical and arranged in diagonal rows directed anterolaterally, parallel with the sulcus terminalis, except at the lingual apex where they are transverse. They have irregular cores of connective tissue ('secondary papillae'), and their epithelium, which is keratinized, may split into fine processes, each being the apex of a secondary papilla; these processes are whitish, owing to a thickened epithelium, the elongated cells being keratinized. The role of these papillae appears to be to increase the friction between the tongue and food, facilitating the movement of particles by the tongue within the oral cavity.

Fungiform papillae (12.54, 58). These are more frequent than vallate; they occur mainly on the lingual margin but also irregularly on the dorsum, where they may occasionally be numerous. They differ from filiform papillae by their larger size, rounded shape and deep red colour; each usually bears one or more taste buds on its apical surface.

Foliate papillae (12.54) (folia linguae). Lying bilaterally, these are two zones, each formed by a series of red, leaf-like mucosal ridges at the sides of the tongue near the sulcus terminalis; they bear numerous taste buds.

Vallate papillae (12.54). Large cylindrical structures, varying in number from 8 to 12 on the dorsum of the tongue; they form a V-shaped row immediately in front of the sulcus terminalis. Each papilla, 1–2 mm in diameter, is encompassed by a slight circular elevation (vallum or wall) in the mucosa separated from the papilla by a circular sulcus (12.59). The papilla is narrower at its base than its apex. The entire structure is covered with stratified squamous epithelium; taste buds (p. 1312) abound in both walls of the sulcus, and small mucoserous glands (of von Ebner) open into the sulcal base.

Other papillae. The epithelium of the tongue has a highly folded interface with the underlying connective tissue, a condition similar to that of the epidermis (12.57). The connective tissue papillae are sometimes termed *papillae simplices*; they are present beneath the entire tongue surface including the mucosal papillae described above and this arrangement serves to increase the anchorage of the epithelium to the underlying tissues.

LINGUAL MUSCULATURE

The tongue is divided by a median fibrous septum, attached to the body of the hyoid bone. In each half are both the extrinsic and intrinsic muscles, the former extending outside the tongue, the latter wholly within it.

Extrinsic muscles (12.60, 61, 67)

These (12.94B) include the *genioglossus*, *hyoglossus*, *styloglossus*, *chondroglossus* and *palatoglossus* muscles.

Genioglossus. This is triangular in sagittal section, lying near and parallel to the midline; it arises from a short tendon attached to the superior genial tubercle behind the mandibular symphysis, above the origin of the geniohyoid. From this point it fans out backwards and upwards. The inferior fibres of genioglossus are attached by a thin aponeurosis to the upper anterior surface of the hyoid body near the midline, a few fasciculi passing between hyoglossus and chondroglossus to blend with the pharyngeal middle constrictor; intermediate fibres pass backwards into the posterior tongue, and superior fibres ascend forwards to enter the whole length of the ventral surface of the tongue from root to apex, intermingling with the intrinsic lingual muscles. The muscles of opposite sides are separated posteriorly by the lingual septum (p. 1724); anteriorly they are variably blended by decussation of fasciculi across the midline. Doran & Baggett (1972) considered that no fibres reach the lingual apex in man or other mammals.

Actions. Genioglossus brings about the forward traction of the tongue to protrude its apex from the mouth. Acting bilaterally, the two muscles depress the central part of the tongue, making it concave from side to side. Acting unilaterally, the tongue diverges to the opposite side.

Hyoglossus. Thin and quadrilateral, this muscle is attached to the whole length of the greater cornu and the front of the body of the hyoid bone, passing almost vertically up to enter the side of the tongue between styloglossus laterally and the inferior longitudinal muscle medially. Fibres arising from the hyoid body overlap those from the greater cornu.

Relations. Hyoglossus is related at its *superficial surface* with: the digastric tendon, stylohyoid, styloglossus and mylohyoid, the lingual nerve and submandibular ganglion, the sublingual gland, the deep part of the submandibular gland and duct, the hypoglossal nerve and the deep lingual vein. By its *deep surface* it is related with: the stylohyoid ligament, genioglossus, inferior longitudinal muscle, lingual artery and glossopharyngeal nerve. Postero-inferiorly it is separated from the middle constrictor by the lingual artery; this part of the muscle is in the lateral wall of the pharynx, below the palatine tonsil. Passing deep to the muscle's posterior border are, in descending order: the glossopharyngeal nerve, stylohyoid ligament and lingual artery.

Action. The hyoglossus depresses the tongue.

Chondroglossus. Sometimes described as a part of hyoglossus,

it is separated from it by some fibres of genioglossus which pass to the side of the pharynx. It is about 2 cm long, arising from the medial side and base of the lesser cornu and the adjoining part of the hyoid body and ascending to merge into the intrinsic musculature between the hyoglossus and genioglossus. A small slip occasionally springs from the cartilago triticea and enters the tongue with the posterior fibres of hyoglossus.

Action. Chondroglossus assists hyoglossus in depressing the tongue.

Styloglossus. The shortest and smallest of the three styloid muscles, it arises from the anterolateral aspect of the styloid process near its apex, and from the styloid end of the stylomandibular ligament. Passing down and forwards, it divides at the side of the tongue into a longitudinal part, which enters the tongue dorsolaterally to blend with the inferior longitudinal muscle in front of the hyoglossus, and an oblique part, overlapping the hyoglossus and decussating with it.

Action. Styloglossus draws the tongue up and backwards.

Nerve supply. Excepting palatoglossus, which is innervated by the cranial accessory/vagal component of the pharyngeal plexus (p. 1252), all extrinsic lingual muscles are supplied by the hypoglossal nerve.

Palatoglossus. This muscle is closely associated with the soft palate in function and innervation, and is described with the other palatal muscles (p. 1690).

Intrinsic muscles (12.60)

These are the bilateral superior and inferior longitudinal, the transverse and the vertical lingual muscles.

Superior longitudinal muscle. A thin stratum of oblique and longitudinal fibres lying beneath the dorsal lingual mucosa, this muscle extends forwards from the submucous fibrous tissue near the epiglottis and from the median lingual septum to the lingual margins, some fibres being inserted into the mucous membrane.

Inferior longitudinal muscle. A narrow band close to the inferior lingual surface between genioglossus and hyoglossus, this extends from the lingual root to the apex, some of its posterior fibres being connected to the body of the hyoid bone; anteriorly it blends with the styloglossus.

Transverse muscle. It passes laterally from the median fibrous septum to the submucous fibrous tissue at the lingual margin, blending with palatopharyngeus (p. 1690).

Vertical muscle. This extends from the dorsal to the ventral aspects of the tongue in the borders of its anterior part.

Nerve supply. All intrinsic lingual muscles are supplied by the hypoglossal nerve.

Actions. The intrinsic muscles alter the shape of the tongue; thus, the superior and inferior longitudinal muscles tend to shorten it; but the former also turns the apex and sides upwards to make the dorsum concave, while the latter pulls the apex down to make the dorsum convex. The transverse muscle narrows and elongates the tongue; the vertical muscle makes it flatter and wider. Acting alone or in pairs and in endless combination, they give the tongue precise and highly varied mobility, important not only in alimentary function but also in speech (p. 1651).

MICROSTRUCTURE OF THE TONGUE

The tongue consists largely of skeletal muscle, partly invested by mucosa. The *lingual mucosa* of the inferior surface is thin, smooth and like that in much of the rest of the oral cavity. The mucosa of the pharyngeal part of the dorsum contains many lymphoid follicles, each follicle forming a rounded eminence, central in which is the minute orifice of a funnel-shaped recess. Many round or oval lymphoid nodules, each encapsulated by submucous fibrous tissue, surround each recess, which receives the ducts of mucous glands in its floor. In the oral part the dorsal mucosa is somewhat thicker than ventrally and laterally; it is adherent to muscular tissue, and covered by numerous *papillae* (p. 396). It consists of connective tissue (*lamina propria*) and stratified squamous epithelium, which also covers each papilla. The lamina propria is a dense fibrous connective tissue, with numerous elastic fibres, united to similar tissue which spreads between the lingual muscle fasciculi. It contains the ramifications of numerous vessels and nerves from which the papillae are supplied, and also large lymph plexuses and lingual glands. The epithelium varies from parakeratinized stratified squamous epithelium posteriorly, to fully keratinized epithelium overlying the filiform papillae more anteriorly; these features appear to be related to the fact that the apex of the tongue is subject to greater dehydration than the posterior and ventral parts and is more abraded during mastication.

Lingual glands

These are of mucous, serous and mixed types. The *mucous glands* are like the labial and buccal glands in structure; they are numerous in the postsulcal region but are also present at the apex and margins. The *anterior lingual salivary glands* lie at the ventral surface of the apex (**12.62**), one on each side of the frenulum, where they are covered by mucosa and a muscular fasciculus derived from the styloglossus and inferior longitudinal muscles. From 12 mm to 20 mm long and about 8 mm broad, each has mucous and serous alveoli and opens by three or four ducts on the inferior surface of the lingual apex. The fine structure of the human *deep posterior lingual glands* has been described in detail by Testa Riva et al (1985).

The *serous glands* (of von Ebner, **12.59**) occur near the taste buds, their ducts opening mostly into the sulci of vallate papillae. They are racemose, the main duct dividing into several channels ending in acini. Their secretion is watery, probably assisting in gustation by spreading substances over the taste area and then washing them away afterwards. The pyramidal shape and ultrastructure of the secretory cells of the acini are similar to those of serous cells elsewhere (see also Testa Riva et al 1985).

The *lingual septum* is a median fibrous partition extending through the length of the tongue but it does not quite reach the dorsum. It is an attachment of the transverse lingual muscles and appears prominently in coronal sections. Posteriorly it extends laterally to form the *hyoglossal membrane*, connecting the lingual root to the hyoid bone, and the inferior fibres of the genioglossi are attached to it.

LINGUAL VESSELS AND NERVES (12.62)

Vessels

The main **artery** is the lingual branch of the external carotid (p. 1516, **10.76**) but the tonsillar and ascending palatine branches of the facial and ascending pharyngeal arteries also supply the lingual root. In the vallecula (p. 1642) epiglottic branches of the superior laryngeal artery anastomose with the inferior dorsal branches of the lingual artery. Lingual muscles are supplied from this rich anastomotic network and there is a very dense submucosal plexus (Combelles 1974). The **veins** are described on p. 1580 and **lymph vessels** on p. 1613.

Nerves

The *sensory nerves* are:

- the lingual branch of the mandibular nerve for general sensation in the presulcal region (p. 1247, **8.339, 357**);
- the chorda tympani branch of the facial nerve (p. 1246), running in the sheath of the lingual nerve, for gustation in the presulcal region exclusive of the vallate papillae (p. 1313); its sensory fibres are derived from the nervus intermedius (p. 1243);
- the lingual branch of the glossopharyngeal nerve (p. 1249), distributed to the postsulcal mucosa of the lingual base and sides and to the vallate papillae and mediating general and gustatory sensation;
- the superior laryngeal nerve (vagus) (p. 1253), which sends fine branches to the root immediately in front of the epiglottis.

The problem of proprioception in the tongue has been reviewed by Fitzgerald and Sachithanadan (1979). Muscle spindles occur in monkeys (Bowman 1968) and in mankind (e.g. Nakayama 1944; Cooper 1953; Kubota et al 1975), as also confirmed in extensive simian material by the above reviewers. The peripheral route from these undoubted receptors is not clear, though it is perhaps in the lingual or hypoglossal nerves and by cervical spinal nerves communicating with the latter. In monkeys Fitzgerald and Sachithanadan presented strong evidence indicating the hypoglossal nerve as the main proprioceptor route for the intrinsic and extrinsic

musculature, many fibres leaving it to enter the second and third cervical anterior primary spinal rami.

The *motor innervation* to all tongue muscles except palatoglossus is from the hypoglossal nerve (p. 1256); palatoglossus receives its supply from the pharyngeal plexus (vagus and cranial accessory, see p. 1252).

The *parasympathetic innervation* of the various glands of the tongue is from the chorda tympani branch of the facial nerve, synapsing in the submandibular ganglion and distributing to the tongue mucosa via the lingual nerve branches. The *sympathetic supply* to lingual glands and vessels enters the tongue through plexuses around its arteries, arising from the carotid plexus (p. 1300). In the postsulcal region, isolated nerve cells have been observed, perhaps postganglionic parasympathetic neurons, **probably** innervating glandular tissue and perhaps vascular smooth muscle (Chu 1968).

CONGENITAL ABNORMALITIES OF THE TONGUE

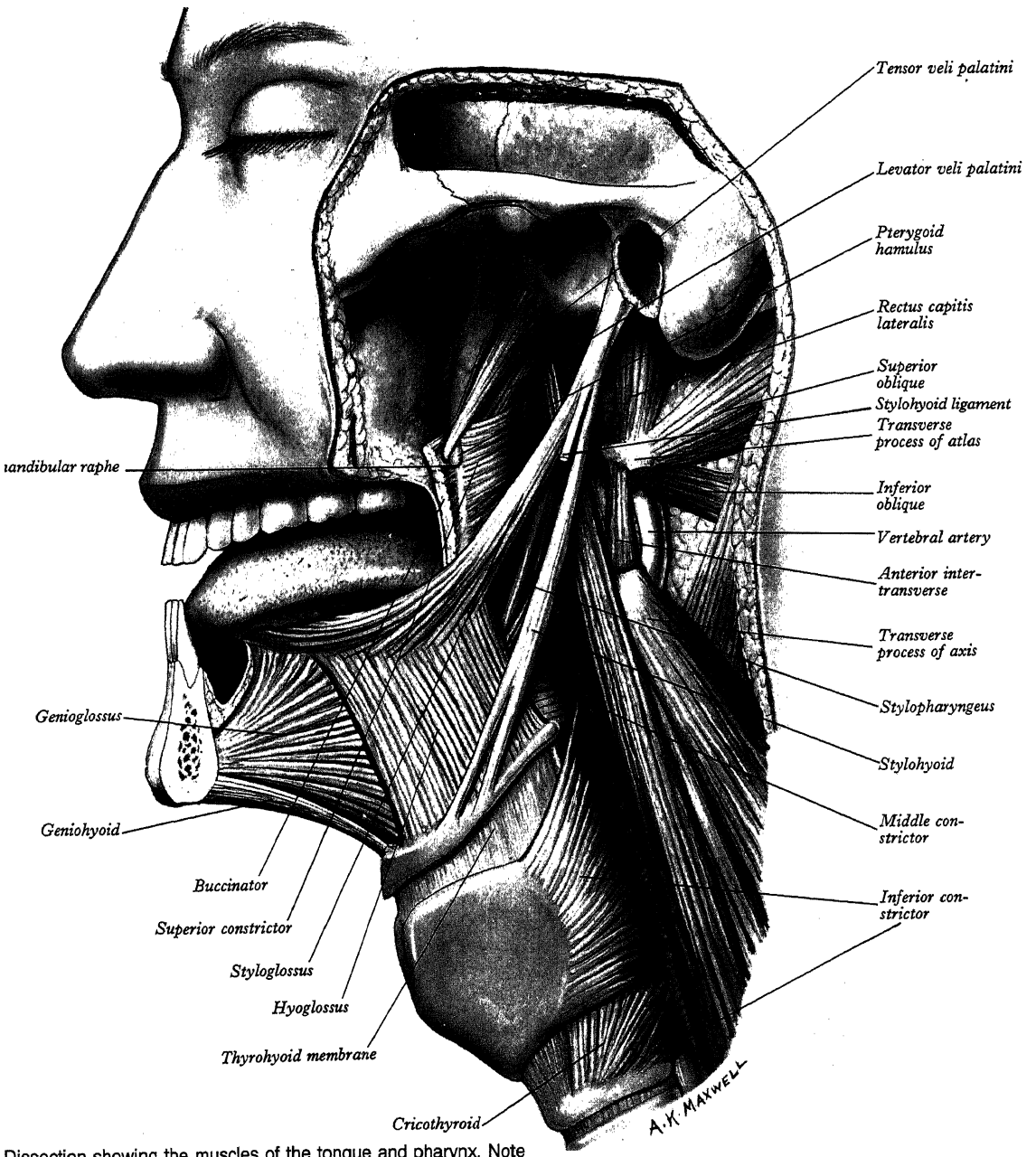
Congenital cysts and fistulae may develop from the persistent remains of the thyroglossal duct (p. 176). Failure of the thyroid gland to migrate out of the tongue may result in its retention as a lingual thyroid in the posterior, postsulcal region. The attachment of the genioglossi to the genial tubercles behind the mandibular symphysis prevents the tongue from sinking back and obstructing respiration; therefore, anaesthetists pull forward the mandible to obtain the full benefit of this connection.

OROPHARYNGEAL ISTHMUS

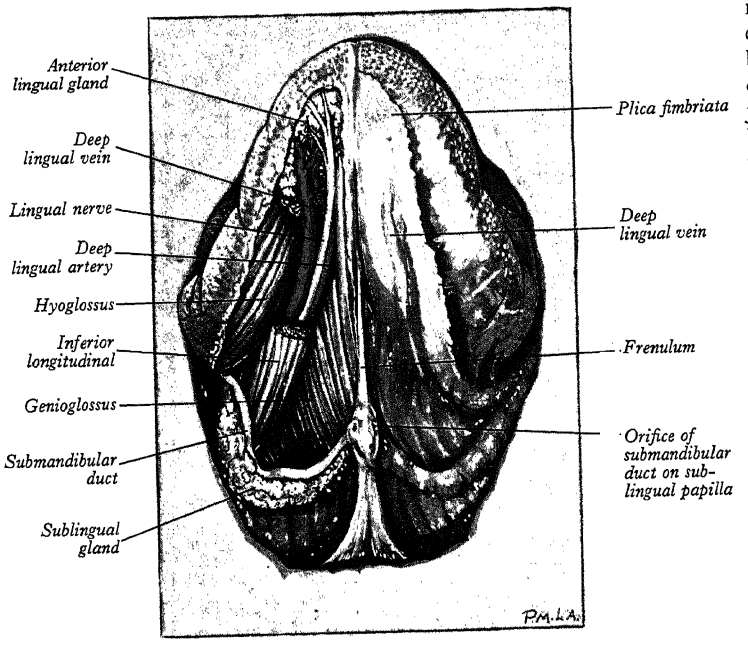
The aperture of communication between the mouth and pharynx, the *oropharyngeal isthmus* (**12.56**) is situated between the soft palate and the lingual dorsum, bounded at the sides by the palatoglossal arches. Each *palatoglossal arch* runs down, laterally and forwards, from the soft palate to the side of the tongue; it is formed by the projecting palatoglossus (p. 1690) with its covering mucous membrane. The approximation of the arches, to shut off the mouth from the oropharynx, is essential to deglutition (p. 1730).

PHARYNX (12.1, 3, 63–69)

The pharynx, situated behind the nasal cavities, mouth and larynx,



12.61 Dissection showing the muscles of the tongue and pharynx. Note that the palatoglossus is not shown here, but is depicted in **12.67**.

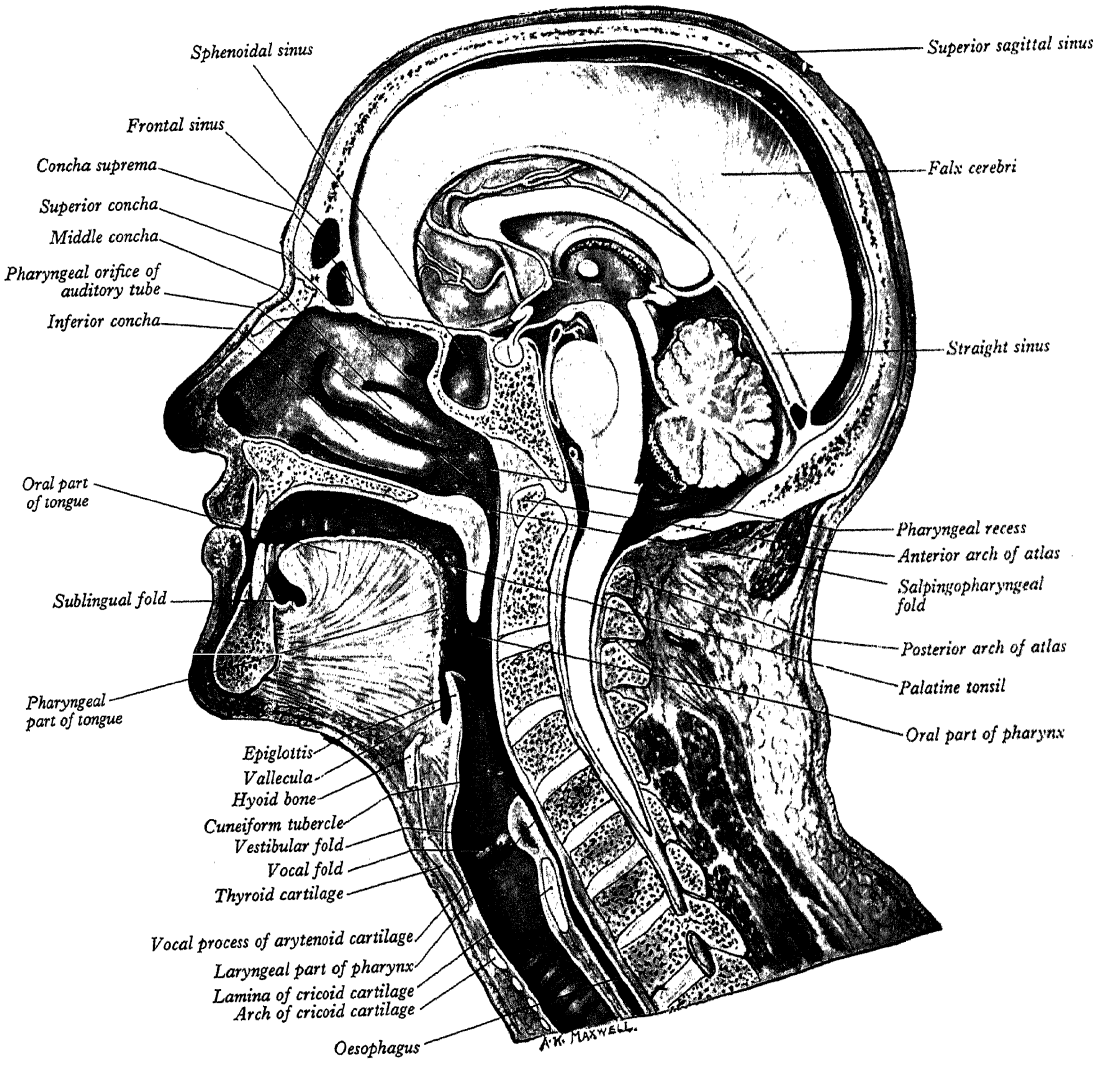


12.62 Dissection of the inferior surface of the tongue, also showing the sublingual glands and submandibular duct openings. On the right side (left side of figure) the mucous membrane has been removed and the inferior longitudinal muscle has been divided and partially resected.

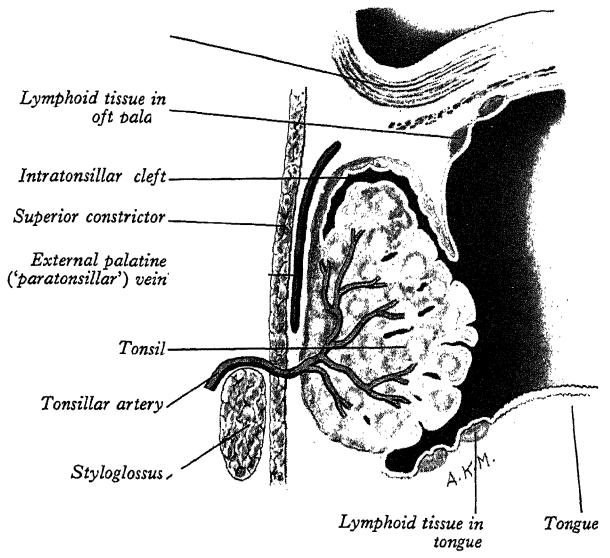
is a musculomembranous tube, 12–14 cm long, extending from the cranial base to the level of the sixth cervical vertebra and the lower border of the cricoid cartilage where it is continuous with the oesophagus. Its width is greatest superiorly, measuring 3.5 cm; at its junction with the oesophagus it is reduced to about 1.5 cm, this being the narrowest part of the alimentary canal (except for the vermiform appendix). It is limited **above** by the posterior part of the sphenoid body and the basilar part of the occipital bone; **below**, it is continuous with the oesophagus; **behind**, loose connective tissue separates it from the cervical part of the vertebral column and prevertebral fascia covering longus colli and capitis; **in front**, it opens into the nasal cavity, mouth and larynx, its anterior wall being therefore incomplete. It is attached, from above downwards on each side to: the medial pterygoid plate, pterygomandibular raphe, mandible, tongue, hyoid bone, thyroid and cricoid cartilages; **laterally**, it communicates with the tympanic cavities via the pharyngotympanic (auditory) tubes and is related to the styloid processes and their muscles, the common, internal and external carotid arteries, and some of the branches of the last named. The pharynx has three parts: nasal, oral and laryngeal (**12.63**).

NASAL PART OF THE PHARYNX (NASOPHARYNX)

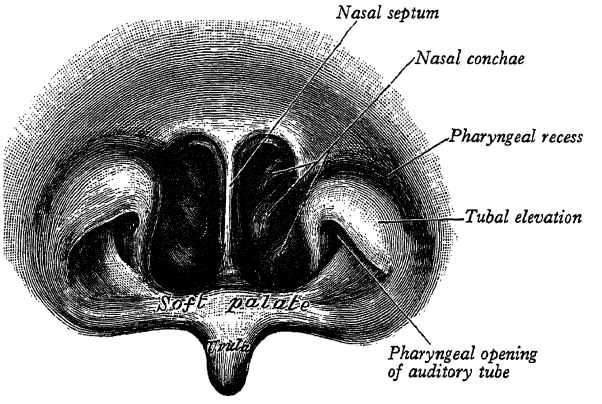
The nasopharynx (**12.63, 65, 67**) lies above the soft palate and behind the *posterior nares (choanae)* which allow free respiratory passage between the nasal cavities and the nasopharynx. The nasal septum separates the two posterior nares (**12.65**), each of which measures approximately 25 mm vertically and 12 mm transversely. Just within these openings lie the posterior ends of the inferior and middle



12.63 Sagittal section through the nose, mouth, pharynx and larynx. Where it divides the skull and the brain, the section passes slightly to the left of the median plane but, below the base of the skull, it passes slightly to the right of the median plane.



12.64 Coronal section through the palatine tonsil.



12.65 Ventral boundary of the nasal part of the pharynx, as seen in posterior rhinoscopy.

turbinates (12.64). Except for the soft palate the walls of the nasopharynx are static and its cavity is never obliterated, in which respect it differs from the oral and laryngeal parts and resembles the nasal cavities. Between the posterior border of the soft palate and the posterior pharyngeal wall the nasal and oral parts of the pharynx communicate through the *pharyngeal isthmus*, which is closed during swallowing by the elevation of the soft palate and constriction of the palatopharyngeal sphincter (p. 1730). The nasopharynx has a roof, a posterior wall, two lateral walls and a floor.

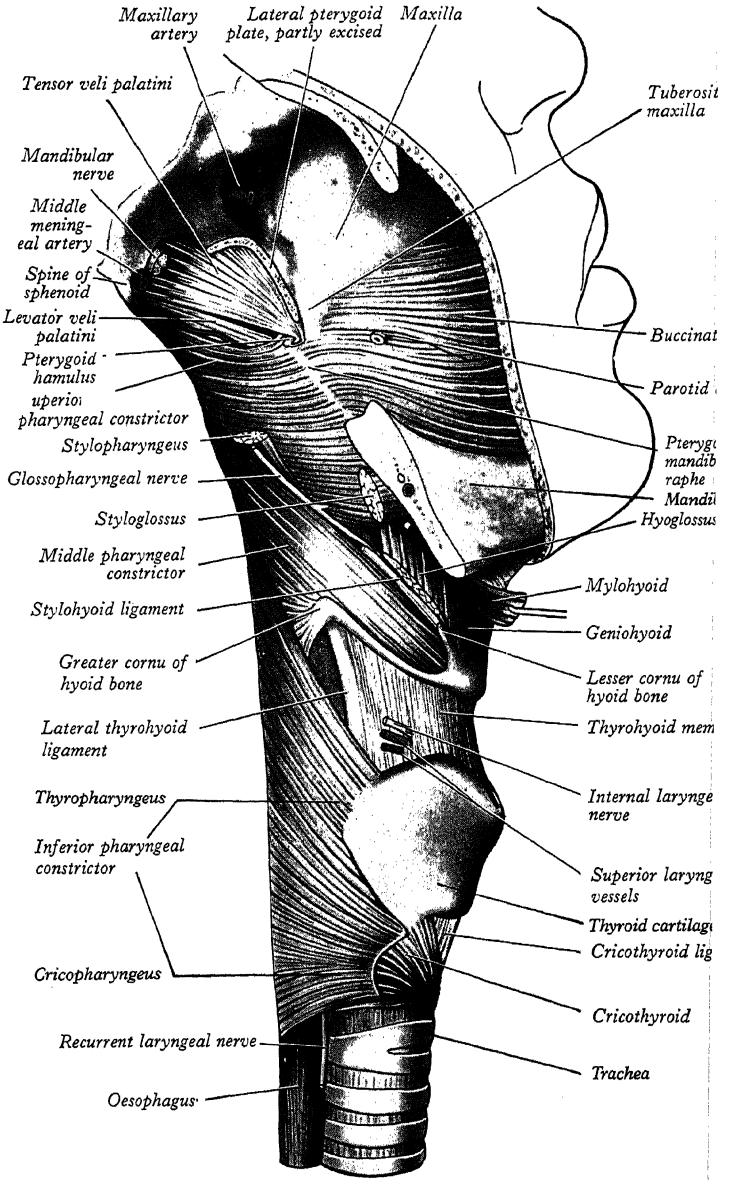
The *roof* and *posterior wall* together form a continuous, concave slope leading down from the nasal septum to the oropharynx, bounded above by mucosa overlying the posterior part of the body of the sphenoid and further back by the basilar part of the occipital bone as far as the pharyngeal tubercle. Following the posterior wall further downwards, the mucosa overlies the pharyngobasilar fascia and the upper fibres of the superior constrictor, and behind these, the anterior arch of the atlas. A lymphoid mass, the *nasopharyngeal tonsil*, lies in the mucosa of the upper part of the roof and posterior wall in the midline (see below; also p. 1374).

The *lateral walls* of the nasopharynx have a number of important surface features. On either side each receives the opening of the *pharyngotympanic tube* (also termed the auditory or Eustachian tube), situated 10–12 mm behind and a little below the level of the inferior nasal turbinate's posterior end (12.63, 65, 67). The tubal aperture is approximately triangular in shape, bounded above and behind by the *tubal elevation* consisting of mucosa overlying the protruding pharyngeal end of the tubal cartilage (p. 1374); the prominent posterior margin of this elevation facilitates the introduction of catheters passed along the floor of the nasal cavity for the intubation of the pharyngotympanic tube.

Behind the tubal opening, a vertical *salpingopharyngeal fold* of mucosa descends from the tubal elevation, covering the salpingopharyngeus muscle in the wall of the pharynx. In front of the aperture, a smaller *salpingopalatine fold* extends from the anterosuperior angle of the tubal elevation to the soft palate. The levator veli palatini, entering the soft palate, produces an elevation of the mucosa immediately below the tubal opening (12.63, 67). In the mucosa immediately posterior to the opening of the pharyngotympanic tube is a small mass of lymphoid tissue, the (bilateral) *tubal tonsils*. Further behind the tubal elevation the lateral wall has a variable depression, the *pharyngeal recess* or *fossa of Rosenmüller* (extensively surveyed by Khoo et al 1969). The *floor* of the nasopharynx is formed by the upper surface of the soft palate.

Nasopharyngeal tonsil

The nasopharyngeal or pharyngeal tonsil is defined as a collection of lymphoid tissue in the mucosa of the nasopharyngeal roof and posterior wall (see above). Like other components of the lymphoid



12.66 The buccinator and the muscles of the pharynx.

tissue annulus encircling the pharynx (Waldeyer's ring, p. 1729), it belongs to the category of mucosa-associated lymphoid tissue (MALT: see p. 1442, and below). When the nasopharyngeal tonsil is enlarged, it is commonly referred to as the adenoid or adenoids, and in the past, Luschka's tonsil (Bershof et al 1987; p. 1447).

The nasopharyngeal tonsil hangs from the roof of the nasopharynx. In surface view it is an oblong, truncated pyramid, its apex pointing towards the nasal septum and its base at the junction of the roof and posterior wall of the nasopharynx. The anterior border is vertical, parallel to the posterior nares, while the posterior border gradually merges into the posterior pharyngeal wall. The lateral borders slope downwards and medially. The free surface is marked by folds radiating forwards and laterally from a median blind recess extending backwards and up, the *pharyngeal bursa* (bursa of Luschka), developmentally the rostral end of the notochord. The number and position of the folds and of the deep fissures separating them vary. A median fold may pass forwards from the pharyngeal bursa towards the nasal septum, or instead a fissure may extend forwards from the bursa, dividing the nasopharyngeal tonsil into two distinct halves (reflecting its paired developmental origins, p. 176). The fissures passing forwards are often curved with their convexity directed outwards, while those near the base of the tonsil are generally straight and nearly transverse (Symington 1914). The size of the nasopharyngeal tonsil is variable according to age (see below), individuality and changes involving hypertrophy and inflammation.

Postnatal development. The prenatal origins and growth of the nasopharyngeal tonsil are described on page 176. After birth the nasopharyngeal tonsil increases rapidly in size in the first few years of life, but there is no unanimous opinion on the time course of its postnatal progression. Its developmental peak has been suggested by various authors to be the second or third year (Hollender & Szanto 1945), the fifth year (Linder-Aronson 1983), the fifth or sixth year (Lion 1950) and between the fifth and tenth year (Meyer 1870). All authors describe the involution or atrophy of the nasopharyngeal tonsil at puberty, although hypoplasia may still occur in adults up to the seventh decade (Hollender & Szanto 1945; Yeh 1962). Using lateral skull radiographs, Linder-Aronson (1983) observed two peaks in its size, one, the greater, occurring at 5 years, and the second between 10 and 11. Relative to the volume of the nasopharynx, the size of the tonsil is largest at 5 years, a finding which could account for the frequency of nasal breathing problems in preschool children, and the incidence of adenoidectomy in this age group.

In the literature, nasopharyngeal tonsil hypertrophy has been commonly associated with maxillary growth abnormalities leading to discrepancies in dental occlusion. However, no causal relationship between enlarged nasopharyngeal tonsils and maxillary abnormalities has been convincingly demonstrated. Similarly, nasopharyngeal hypertrophy has been implicated in the aetiology of chronic otitis media with effusion in children, but Hibbert and Stell (1982) found no statistically significant difference in the radiological size of the nasopharyngeal tonsil in children with this condition compared with an age and gender matched control group. Furthermore, Gates et al (1989) found no relationship between preoperative nasopharyngeal tonsil size and the rate of resolution of chronic otitis media with effusion following surgery. Nevertheless, surgical removal of the nasopharyngeal tonsil in children with chronic otitis media with effusion has been shown to improve resolution of this disease in children (Maw & Parker 1993).

Microstructure. The nasopharyngeal tonsil is composed of a rather modified nasopharyngeal epithelium overlying mucosa-associated lymphoid tissue. Details of its microscopic organization are given on page 1448.

Vessels. *The arterial supply* of the nasopharyngeal tonsil derives from branches of the external carotid artery, namely the ascending pharyngeal artery, the ascending palatine artery, the tonsillar branches of the facial artery, the pharyngeal branch of the maxillary artery and the artery of the pterygoid canal. In addition, a nutrient or emissary vessel to the neighbouring bone, the *basisphenoid artery*, a branch of the inferior hypophysial arteries, supplies the bed of the nasopharyngeal tonsil and is a possible cause of persistent postadenoidectomy haemorrhage in some patients. Numerous communicating veins drain the nasopharyngeal tonsil into the internal submucous and external pharyngeal venous plexuses (p. 1580).

Lymphatics. As with other types of mucosa-associated lymphoid tissue, there are no afferent lymphatics. Efferent lymphatics commence in a closed plexus around each lymphoid follicle, pass into the connective tissue septa, pierce the hemicapsule and drain to the upper deep cervical lymph nodes directly, or indirectly through the retropharyngeal lymph nodes.

Innervation. The nasopharynx is innervated by the pharyngeal plexus (p. 1252) situated mainly in the buccopharyngeal fascia. In addition, a small part of the nasopharynx behind the opening of the pharyngotympanic tube receives a sensory supply from the pharyngeal branch of the maxillary nerve.

ORAL PART OF THE PHARYNX (12.56, 63)

The *oropharynx* extends from the soft palate to the upper border of the epiglottis. It opens into the mouth through the oropharyngeal isthmus, demarcated by the palatoglossal arch, and faces the pharyngeal aspect of the tongue. Its lateral wall consists of the palatopharyngeal arch and palatine tonsil. Posteriorly, it is level with the body of the second and upper part of the third cervical vertebrae. The *palatopharyngeal arch* lies behind the *palatoglossal arch*, projecting more medially than the latter, and descends posterolaterally from the uvula to the lateral wall of the pharynx as a fold of mucosa covering palatopharyngeus (p. 1690). On each side of the oropharynx, between the diverging palatopharyngeal and palatoglossal arches, lies the triangular *tonsillar fossa* or *tonsillar sinus* containing the *palatine tonsil.*

Palatine tonsils

The palatine tonsil (tonsilla palatina) (12.54, 56, 63, 64) is a bilaterally paired mass of lymphoid tissue situated in the lateral wall of the oropharynx and forming part of a protective annulus of lymphoid tissue, the *Waldeyer's ring* (see p. 1729).

The shape of the palatine tonsil is ovoid and its size is variable according to age, individuality and tissue changes leading to hypertrophy and/or inflammation. It is therefore difficult to define its normal appearance. For the first 5 or 6 years of life the tonsils increase rapidly in size, reaching a maximum at puberty when they average 20–25 mm in vertical and 10–15 mm in transverse diameter, projecting conspicuously into the oropharynx (Symington 1914; McNab Jones 1979). Tonsillar involution begins at puberty when the reactive lymphoid tissue starts to undergo atrophic changes, and by old age only a little tonsillar lymphoid tissue remains.

The long axis of the tonsil is directed from above, downwards and backwards. Its *medial* or *free surface* usually presents a pitted appearance. These *pits*, 10–15 in number, lead to a system of blind-ending, often highly branching *crypts*, which extend through the whole thickness of the tonsil and almost reach the connective tissue hemicapsule. In a healthy tonsil the openings of the crypts are fissure-like and the walls of the crypt lumina are collapsed and in contact with each other. The human tonsil is a polycryptic structure, unlike the monocryptic tonsil of some other mammals, e.g. rabbit and sheep (Olah 1978). The branching crypt system reaches its maximum size and complexity during childhood (Fioretti 1957). In the upper part of the medial surface of the tonsil is the mouth of a deep *intratonsillar cleft*, or *recessus palatinus* (Killian 1898), often erroneously termed the *supratonsillar fossa*. It is **not** situated above the tonsil but within its substance (12.63), and the mouth of the cleft is semilunar in shape, curving parallel to the convex dorsum of the tongue in the parasagittal plane. The upper wall of this recess contains lymphoid tissue extending into the soft palate as the *pars palatina of the palatine tonsil* (Hett & Butterfield 1910). After the age of 5 years this embedded part of the tonsil diminishes in size; from the age of 14, there is a tendency for the whole tonsil to retrogress, and for the tonsillar bed to flatten out (Hett 1913). During young adult life a mucosal fold termed the *plica triangularis* (for developmental aspects see p. 176), stretching back from the palatoglossal arch down to the tongue, is infiltrated by lymphoid tissue and frequently represents the most prominent (antero-inferior) portion of the tonsil. However, it rarely persists into middle age.

The *lateral* or *deep surface* of the tonsil spreads downwards, upwards and forwards. Inferiorly, it invades the dorsum of the tongue, superiorly, the soft palate, and, anteriorly, it may extend for some distance under the palatoglossal arch. This deep, lateral aspect is covered by a layer of fibrous tissue, the *tonsillar hemicapsule*, separable with ease for most of its extent from the underlying muscular walls of the pharynx which is formed here by the superior constrictor, with the styloglossus on its lateral side (**12**.63, 66). Antero-inferiorly the hemicapsule adheres to the side of the tongue and to the palatoglossus and palatopharyngeus muscles. In this region the tonsillar artery, a branch of the facial, pierces the superior constrictor to enter the tonsil, accompanied by venae comitantes. An important and sometimes large vein (the external palatine or paratonsillar vein) descends from the soft palate lateral to the tonsillar hemicapsule before piercing the pharyngeal wall (**12**.63); haemorrhage from this vessel, from the upper angle of the tonsillar fossa, may complicate tonsillectomy (Browne 1928). The muscular wall of the tonsillar fossa separates the tonsil from the ascending palatine artery, and, occasionally, from the tortuous facial artery itself (p. 1517) which may be near the pharyngeal wall at the lower tonsillar level. The internal carotid artery lies about 25 mm behind and lateral to the tonsil.

Surface anatomy. The palatine tonsil is too deeply placed to be felt externally, even when enlarged. When the mouth is closed the medial surface of the tonsil touches the dorsum of the tongue. In this position the surface marking of the palatine tonsil on the exterior of the face corresponds to an oval area over the lower part of the masseter muscle, a little above and in front of the angle of the mandible and behind the third lower molar tooth.

Microstructure. The basic structure of the palatine tonsil is that of an accumulation of mucosa-associated lymphoid tissue covered by stratified squamous non-keratinizing epithelium on its oropharyngeal surface, and supported by connective tissue septa arising from the hemicapsule. On the medial oropharyngeal surface the tonsillar epithelium is deeply invaginated to form 10–30 or more crypts. Like other neighbouring masses of mucosa-associated lymphoid tissue forming Waldeyer's ring (see below), the palatine tonsil is a major source of T and B lymphocytes for local mucosal defence. Further details of its immunological functions and microstructure are given on page 1446.

Blood vessels. The **arterial blood supply** to the palatine tonsil derives from branches of the external carotid artery. The principal artery is the *tonsillar artery*, which is a branch of the facial or sometimes the ascending palatine artery. The tonsillar artery and its venae comitantes often lie within the palatoglossal fold; hence a haemorrhage may be caused by interference with this fold during an operation. Additional small tonsillar branches may derive from the following: the ascending pharyngeal artery; the dorsales linguae, branches of the lingual artery, supplying the lower part of the palatine tonsil; the greater palatine artery (a branch of the maxillary artery) supplying the upper part of the tonsil; and the ascending palatine artery, a branch of the facial artery.

The **tonsillar veins** are numerous and emerge from the deep, lateral surface of the tonsil as the *paratonsillar veins*. They pierce the superior constrictor either to join the pharyngeal venous plexus, or to unite to form a single vessel which enters the facial vein.

Lymphatics. Unlike lymph nodes, the tonsils do not possess afferent lymphatics or lymph sinuses (p. 1432), but dense plexuses of fine lymphatic vessels surround each follicle, forming *efferent lymphatics* which pass towards the hemicapsule, pierce the superior constrictor and drain to the upper deep cervical lymph nodes, especially the *jugulodigastric nodes* (p. 1613). Typically, the latter are enlarged in tonsillitis; they then project beyond the anterior border of the sternocleidomastoid muscle and are palpable superficially 1–2 cm below the angle of the mandible. They represent the most common swelling in the neck.

Nerves. The tonsillar region receives its nerve supply through *tonsillar branches of the trigeminal* (*maxillary*) and the *glossopharyngeal nerves*. The maxillary nerve fibres passing through (though not synapsing in) the pterygopalatine ganglion and are distributed through the lesser palatine nerves (p. 1235), which, together with the tonsillar branches of the glossopharyngeal nerve (p. 1249), form a plexus around the tonsil. From this plexus, termed the 'circulus tonsillaris' (Barnes 1923), nerve fibres are also distributed to the soft palate and the region of the oropharyngeal isthmus. The glossopharyngeal nerve additionally supplies, through its tympanic branch, the mucous membrane lining the tympanic cavity. Hence, tonsillitis may be accompanied by pain referred to the ear. The nerve supply to the tonsil is so diffuse that tonsillectomy under local anaesthesia is performed successfully by local infiltration rather than by blocking the main nerves.

WALDEYER'S RING

This annulus of mucosa-associated lymphoid tissue surrounds the openings into the digestive and respiratory tracts and consists antero-inferiorly of the lingual tonsil, laterally the palatine and tubal tonsils, posterosuperiorly the nasopharyngeal tonsil (p. 1728) and smaller collections of lymphoid tissue in the intertonsillar intervals (Waldeyer 1884; Graney 1986).

LARYNGEAL PART OF THE PHARYNX (**12**.63, **11**.1)

The laryngeal part of the pharynx (*laryngopharynx*) extends from the superior border of the epiglottis to the inferior border of the cricoid cartilage, where it becomes continuous with the oesophagus. In its incomplete anterior wall is the laryngeal inlet (p. 1643) and below this the posterior surfaces of the arytenoid and cricoid cartilages.

A small *piriform fossa* on each side of the inlet is bounded medially by the aryepiglottic fold and laterally by the thyroid cartilage and thyrohyoid membrane. Beneath its mucous membrane are the branches of the internal laryngeal nerve which have pierced the thyrohyoid membrane. Foreign bodies may lodge in the fossa and, if the mucous membrane is pierced during their removal, the nerve may be damaged, with consequent anaesthesia of the region. Posteriorly the laryngopharynx extends from the lower part of the third cervical vertebral body to the upper part of the sixth.

MICROSTRUCTURE OF THE PHARYNX

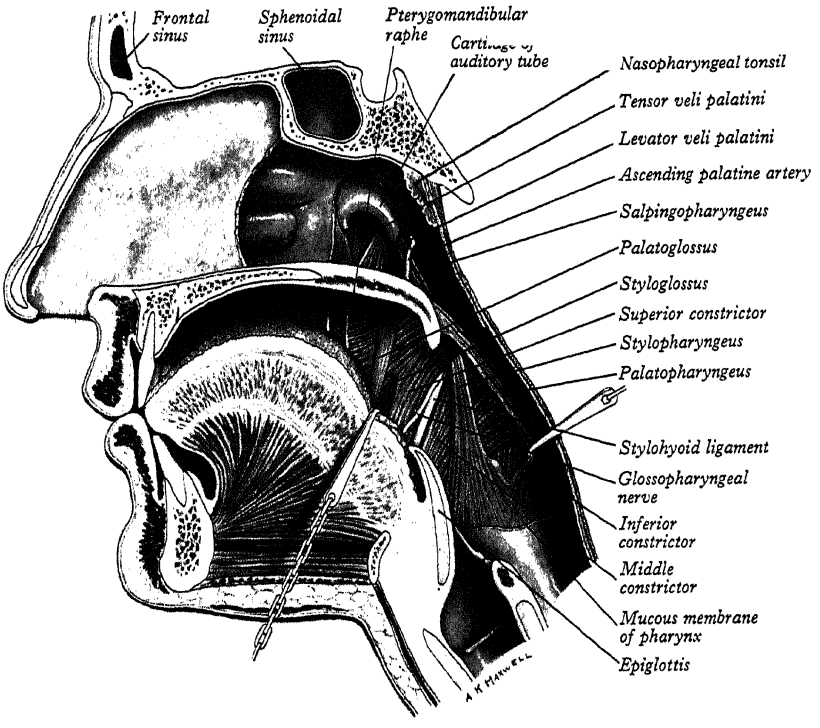
The pharynx wall has, from within outwards, mucous, fibrous and muscular layers, and finally a thin buccopharyngeal fascia external to the constrictor muscles and passing forwards over the pterygomandibular raphe on to the buccinator.

The *mucosa* is continuous with that lining the pharyngotympanic tubes, nasal cavity, mouth and larynx. The nasopharyngeal epithelium is anteriorly ciliated, pseudostratified 'respiratory' in type, with goblet cells and receiving the ducts of mucosal and submucosal seromucous glands. There is a transition in the posterior region of the nasopharynx to non-keratinized stratified squamous epithelium which continues to cover the surfaces of the oropharynx and laryngopharynx. Between the two types of epithelium there is a transitional zone of columnar epithelium with short microvilli instead of cilia. Superiorly this zone adjoins the nasal septum; laterally it passes over the orifice of the pharyngotympanic tube and turns posteriorly at the union of the soft palate and the lateral wall (pp. 1689, 1730). Mucous glands are numerous around the tubal orifices.

The mucosa is supported by an intermediate *fibrous layer*. This is thick above (the *pharyngobasilar fascia*) where muscle fibres are absent, and is firmly connected to the basilar part of the occipital and petrous temporal bones medial to the pharyngotympanic tube and forwards to the posterior border of the medial pterygoid plate and pterygomandibular raphe. As it descends it diminishes in thickness but is strengthened posteriorly by a fibrous band attached to the pharyngeal tubercle of the occipital bone and descending as the median *pharyngeal raphe* of the constrictors. This fibrous layer is really the thick, deep epimysial covering of the muscles and their aponeurotic attachment to the base of the skull; the thinner external part of the epimysium is then the *buccopharyngeal fascia* (p. 796). The muscular coat is described below.

PHARYNGEAL MUSCULATURE (**12**.66–69)

This consists of: three *constrictor* muscles, superior, middle and inferior, and a trio of muscles descending from the styloid process, the cartilaginous torus of the pharyngotympanic tube, and the soft palate, respectively the *stylo-*, *salpingo-* and *palatopharyngei*, all of which pass obliquely into the muscular wall (**12**.67).



12.67 Median sagittal section of the head, showing a dissection of the interior of the pharynx, after the removal of the mucous membrane. The bodies of the cervical vertebrae have been removed and the cut posterior wall of the pharynx then retracted dorsolaterally. The palatopharyngeus is drawn dorsally to show the cranial fibres of the inferior constrictor; the dorsum of the tongue is drawn ventrally to display a part of the styloglossus in the angular interval between the mandibular and the lingual fibres of origin of the superior constrictor.

Superior constrictor. This is a quadrilateral sheet of muscle, thinner and paler than the other two constrictors. It is attached anteriorly to the pterygoid hamulus (and sometimes to the adjoining posterior margin of the medial pterygoid plate), the pterygomandibular raphe, and below to the posterior end of the mylohyoid line of the mandible and by a few fibres to the side of the tongue (**12.66**). These attachments define, respectively, the *pterygopharyngeal*, *buccopharyngeal*, *mylopharyngeal* and *glossopharyngeal* parts of the superior constrictor. Its fibres curve back into the median pharyngeal raphe; some are also prolonged by an aponeurosis to the pharyngeal tubercle on the basilar part of the occipital bone, the superior fibres curving under levator veli palatini and the pharyngotympanic tube and leaving an interval below the cranial base for passage of the pharyngotympanic tube. This interval is limited anteriorly by the medial pterygoid plate and closed by the pharyngobasilar fascia (p. 1729).

A constant band of muscle sweeps backwards from the anterolateral part of the upper surface of the palatine aponeurosis, lateral to levator veli palatini, to blend internally with the superior constrictor near its superior border (**12.69**). This band is the *palatopharyngeal sphincter*; it ridges the pharyngeal wall (*ridge of Passavant*) visibly when the soft palate is elevated (Whillis 1930). It is hypertrophied in cases of complete cleft palate. The change from columnar, ciliated, 'respiratory' epithelium to stratified, squamous epithelium on the superior palatal aspect occurs at the attachment of the palatopharyngeal sphincter to the palate.

Relations. External to the superior constrictor are the prevertebral fascia and muscles, the ascending pharyngeal artery and the pharyngeal venous plexus, glossopharyngeal and lingual nerves, styloglossus, middle constrictor, medial pterygoid, stylohyoid ligament and stylopharyngeus; the internal carotid artery, sympathetic trunk, hypoglossal nerve, internal jugular vein and styloid process are more distant relations. **Internal** are palatopharyngeus, the tonsillar capsule and pharyngobasilar fascia. **Superiorly** it is separated from the cranial base by a crescentic interval containing levator veli palatini, tensor veli palatini and the pharyngotympanic tube. **Inferiorly** its border is separated from the middle constrictor by stylopharyngeus and the glossopharyngeal nerve. **Anteriorly** it is separated from buccinator by the pterygomandibular raphe.

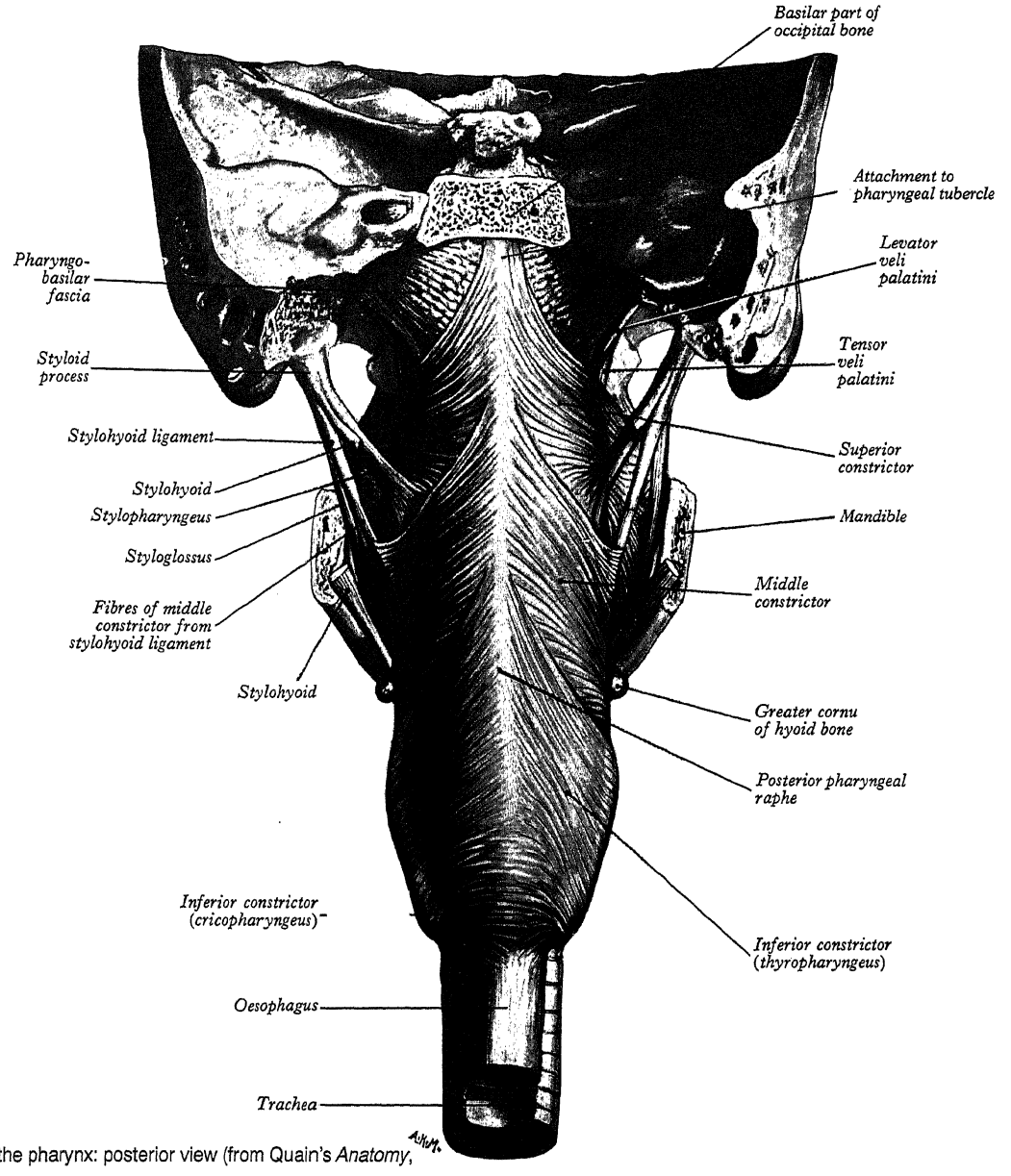
Middle constrictor (**12.66, 68**). This is a fan-shaped sheet attached anteriorly to the lesser cornu of the hyoid and the lower part of the stylohyoid ligament (the *chondropharyngeal* part of the muscle) and to the whole upper border of the greater cornu of the hyoid (the *ceratopharyngeal* part). The lower fibres descend deep to the inferior constrictor to the lower end of the pharynx, the middle fibres pass transversely and the superior fibres ascend and overlap the superior constrictor. It is inserted posteriorly into the median pharyngeal raphe with its opposite fellow.

Relations. Through the small gap between the middle and superior constrictors pass the glossopharyngeal nerve and the stylopharyngeus muscle; between the middle and inferior constrictors pass the internal laryngeal nerve and laryngeal branch of the superior thyroid artery. **Posterior** are the prevertebral fascia, longus colli and longus capitis; **lateral** are the carotid vessels, pharyngeal plexus of nerves and some lymph nodes. Near its hyoid attachment the constrictor is deep to hyoglossus, the lingual artery lying between them. **Internal** are the superior constrictors, stylopharyngeus, palatopharyngeus and the fibrous lamina.

Inferior constrictor. The thickest of the constrictors, this has two parts, cricopharyngeus and thyropharyngeus (**12.66, 68**). It is attached to (**12.65**) the side of the cricoid cartilage between the attachment of cricothyroid and, posteriorly, the articular facet for the inferior thyroid cornu (*cricopharyngeus*). It also arises from:

- the oblique line of the thyroid lamina
- a strip of the lamina behind this
- a fine tendinous band crossing cricothyroid from the inferior thyroid tubercle to the cricoid cartilage
- the inferior cornu (*thyropharyngeus*) by a small slip.

Both parts spread posteromedially to join the opposite muscle in the median pharyngeal raphe. The inferior fibres, which are horizontal, blend with the circular oesophageal fibres round the narrowest part of the pharynx; the rest ascend obliquely and overlap the middle constrictor. During swallowing the cricopharyngeus is 'sphincteric' (Fuller et al 1959) and the thyropharyngeus 'propulsive'; failure of relaxation of the cricopharyngeus may cause posterior mucosal herniation between the two parts of the muscle (Killian's dehiscence).



12.68 The muscles of the pharynx: posterior view (from Quain's *Anatomy*, 11th edn).

Relations. The buccopharyngeal fascia is external to the inferior constrictor. **Posterior** are the prevertebral fascia and muscles, **lateral** the thyroid gland, common carotid artery and the sternothyroid, **internal** are the middle constrictor, stylopharyngeus, palatopharyngeus and the fibrous lamina. The internal laryngeal nerve and laryngeal branch of the superior thyroid artery reach the thyrohyoid membrane between the inferior and middle constrictors. The external laryngeal nerve descends on the superficial surface of the muscle, just behind its thyroid attachment and piercing its lower part. The recurrent laryngeal nerve and the laryngeal branch of the inferior thyroid artery ascend internal to its lower border to enter the larynx.

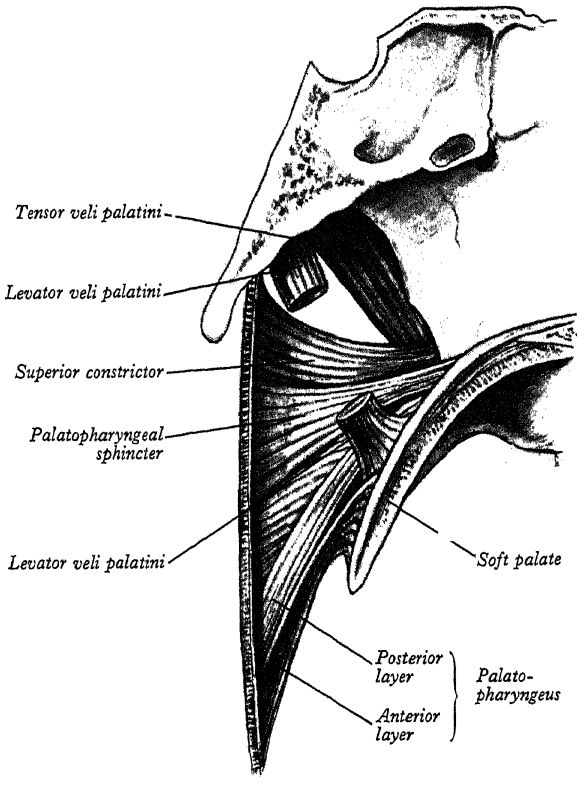
Nerve supply of the constrictors

The constrictors are supplied by the *pharyngeal plexus* (p. 1252), the inferior constrictor also by rami of the external and recurrent laryngeal nerves. The pharynx is largely a branchial derivative (p. 175), hence its motor and sensory supply is through the trigeminal, glossopharyngeal, vagus nerves and cranial accessory. Additionally, glandular tissue in the pharyngeal mucosa and vascular smooth muscle receive an autonomic supply through the pharyngeal plexus. Postganglionic sympathetic fibres reach this plexus from the superior cervical ganglion via special rami; the preganglionic parasympathetic supply issues from the medulla oblongata, chiefly in the glossopharyngeal nerve, which also contains afferents from the oral and laryngeal mucosae, the nasal mucosa being trigeminal territory. The vagus nerve carries branchial efferent fibres for pharyngeal striated musculature but most of these fibres probably emerge from the brainstem in the cranial, bulbar part of the accessory nerve.

The pharyngeal rami of the glossopharyngeal and vagus nerves and of the superior cervical ganglion form a plexus in the connective tissue external to the constrictors, particularly the intermediate muscle (Hovelacque 1927). From the plexus, in which autonomic (sympathetic and parasympathetic) and branchial (efferent and afferent) fibres intermingle, mixed rami ascend and descend exterior to the superior and inferior constrictors, branching into the muscular layer and mucosa. This pattern is common to most primates (Sprague 1944), including mankind; but in some lower primates the plexus is absent or simplified and may lack glossopharyngeal or vagal components. In other mammals arrangements vary; in many there is no plexus, but precise information on the main rami of supply and their exact brainstem sources is lacking. The marked development of the plexus in man and some other primates has been ascribed to phonation; perhaps this is too facile a view, considering the lack of factual evidence.

Actions of constrictors

The constrictors exercise a general sphincteric and peristaltic action in swallowing. For details, see below.



12.69 The muscles of the left half of the soft palate and adjoining part of the pharyngeal wall in sagittal section. Part of the levator veli palatini has been removed to reveal the palatopharyngeal sphincter. The soft palate is cut sagittally. (Dissection by the late James Whillis, Department of Anatomy, Guy's Hospital Medical School, London.)

Stylopharyngeus (12.3, 66–68). A long slender muscle, cylindrical above and flat below, it arises from the medial side of the base of the styloid process, descending along the side of the pharynx and passing between the superior and middle constrictors to spread out beneath the mucous membrane. Some fibres merge into the constrictors and the lateral glosso-epiglottic fold, others are attached with palatopharyngeus to the posterior border of the thyroid cartilage. The glossopharyngeal nerve curves round the posterior border and the lateral side of stylopharyngeus, passing between the superior and middle constrictors to the tongue.

Nerve supply. A branch of the glossopharyngeal nerve.

Action. Elevation of the pharynx in swallowing and speech (see below).

Salpingopharyngeus (12.3, 67). This muscle arises from the inferior part of the cartilage of the pharyngotympanic tube near the tube's pharyngeal opening to pass downwards and blend with palatopharyngeus.

Nerve supply. The pharyngeal plexus.

Action. Elevation of the upper lateral wall of the pharynx, i.e. the part above the attachment of stylopharyngeus. For its role in swallowing, see below.

Palatopharyngeus (12.67, 69). This is described with the other palatal muscles on page 1690.

Vessels

The **pharyngeal arterial supply** is from the ascending pharyngeal, ascending palatine and tonsillar branches of the facial artery, branches of the maxillary artery (greater palatine, pharyngeal and artery of the pterygoid canal) and dorsal lingual branches of the lingual artery. The **veins** form a plexus connected above with the pterygoid plexus and draining below into the internal jugular and facial veins.

The **lymph vessels** are described on pages 1612, 1623.

Nerves

Innervation is derived mainly from the pharyngeal plexus (p. 1252). The principal **motor** element is the cranial part of the accessory nerve, which, through vagal branches, supplies all pharyngeal and palatal muscles except stylopharyngeus (glossopharyngeal nerve) and tensor veli palatini (mandibular nerve). The main **sensory** nerves are the glossopharyngeal and vagal; much nasopharyngeal mucosa is supplied by the maxillary nerve (via the pterygopalatine ganglion); the mucosa of the soft palate and tonsil is supplied by the lesser palatine and glossopharyngeal nerves. Proprioceptor endings have not been convincingly identified in the pharynx (Bossy & Vidić 1967).

PALATINE MOVEMENTS

Movements of the palate are essential to swallowing, blowing and speech; all require variable degrees of closure of the pharyngeal isthmus (p. 1730). Closure is maximal in blowing out through the mouth, when the prevention of escape of air through the nose is needed. In deglutition, closure prevents regurgitation into the nasopharynx. In speech, closure is maximal in the production of explosive consonants (e.g. *b*, *p*). Closure of the isthmus is effected as follows: the levatores veli palatini pull the soft palate up and back towards the posterior pharyngeal wall, while simultaneously the palatopharyngeal sphincter raises the wall to meet the palatine nasopharyngeal surface over a wide area. (It is at the upper limit of this contact area that the epithelium on the upper surface of the soft palate changes from respiratory to stratified squamous.)

The palatal tensors are active in deglutition rather than speech; by producing a localized anterior depression in the soft palate (p. 1689) they squeeze the bolus against the tongue, aiding its descent in the oropharynx.

MECHANISM OF DEGLUTITION

The ***first stage*** of swallowing is *voluntary*: the anterior part of the tongue is raised and pressed against the hard palate, the movement commencing at the lingual apex and spreading rapidly back. A bolus, formed behind the apex, is thus pushed posteriorly. At the end of this stage the soft palate descends on to the lingual dorsum, helping to grip the bolus. Lingual movements are effected by the intrinsic muscles, especially the superior longitudinal and transverse. Simultaneously the hyoid bone is moved up and forwards by the geniohyoid, mylohyoid, digastric and stylohyoid. The postsulcal part of the tongue is drawn up and back by the styloglossi and the palatoglossal arches are approximated by the palatoglossi, pushing the bolus through the oropharyngeal isthmus into the oropharynx, where the second, *involuntary*, stage begins. In swallowing fluids, the intrinsic lingual muscles squirt liquid backwards in the mouth, after which mylohyoid contraction bulges the lingual base into the oropharynx. In swallowing solids only the mylohyoid action is needed, except in cleansing the mouth of saliva and debris after a bolus is swallowed (Whillis 1946). Hiiemae et al (1978) analysed lingual and hyoid activity in swallowing, using the cat and the opossum as models. By cineradiography and electromyography (EMG) they described the cyclic activities of hyoid muscles, delineating 'envelopes' of movement. They regard lingual movements as largely transportive, the precise combination of lingual and hyoid movements depending on the nature of the ingested material. The extension of these studies to primates is awaited with interest.

In the **second stage**, the soft palate is elevated (by levator muscles), tightened (tensor muscles) and firmly approximated to the posterior pharyngeal wall by the palatopharyngeal sphincter (p. 1690) and the upper part of the superior constrictor. The pharyngeal isthmus closes tightly to prevent food from ascending into the nasopharynx. Meanwhile the larynx and the pharynx are drawn up, behind the hyoid bone, by stylopharyngeus, salpingopharyngeus, thyrohyoid and palatopharyngeus. Simultaneously the aryepiglottic folds are approximated and the arytenoid cartilages drawn up and forwards by the aryepiglottic, oblique arytenoid and thyroarytenoid muscles, excluding the bolus from the larynx. Partly by gravity and partly by successive contractions of the superior and middle constrictors, the bolus slips over the epiglottis (now bent back on to the laryngeal aditus), the closed laryngeal inlet and posterior arytenoid surfaces into the lowest part of the pharynx. Its passage is facilitated by the palatopharyngei, which shorten the pharynx by elevating it; on contraction, they make the posterior pharyngeal wall into an inclined

plane directed postero-inferiorly, and under this the bolus descends. The aryepiglottic folds provide lateral channels leading from the sides of the epiglottis through the piriform fossae into the oesophagus. They are kept tense and vertical by the backward pull of the posterior crico-arytenoids on the arytenoid cartilages and by the muscles (aryepiglottic and thyroepiglottic) within them, assisted by the cuneiform cartilages which act as passive props. In paralysis of these muscles (which are supplied by the recurrent laryngeal nerves) the laryngeal inlet is not closed in swallowing, the folds sink medially and fluids tend to enter the larynx.

The **last stage** in swallowing is the expulsion, by the inferior constrictors, of the now compressed bolus into the oesophagus (p. 1751). The pump-like action of the pharyngeal muscles in this activity has been described by Buthpitiya et al (1987).

These stages follow on each other, but it is easy to ascertain by palpation of the hyoid bone and laryngeal prominence that, during swallowing, elevation and forward movement of the hyoid precede laryngeal elevation. Note that the thyroid cartilage, and hence the whole larynx, ascends also **relative** to the hyoid, shortening the larynx and causing structures between the hyoid bone and thyroid cartilage to bulge posteriorly into the larynx above the vestibular folds. This also increases the curvature of the epiglottis, especially in its lower part, aiding stenosis of the laryngeal aditus during swallowing (see Fink & Martin 1977).

The evidence for the foregoing analysis comes from various sources: radiological studies, the effects of known paralyses, EMG, ultrasound analysis (Shawker et al 1984) and cineradiography. Swallowing is, however, a highly complex process, depending on highly patterned neural control, and it is not surprising that some disagreement over its detail still persists. For full critiques of the literature consult Bosma (1957), Doty (1968), Hiiemae (1978), and Buthpitiya et al (1987).

OESOPHAGUS

This tubular part of the alimentary tract, continuing from the pharynx, passes through the neck and thorax to the abdominal cavity. It is described with the abdominal alimentary tract on page 1751.

ABDOMEN: GENERAL ORGANIZATION

Abdominal boundaries

The abdomen extends from the diaphragm to the base of the pelvis (**12**.70, 71), comprising the *abdomen proper* and the *lesser pelvis*, continuous with each other at the plane of the inlet into the lesser pelvis, which is bounded by the sacral promontory, arcuate lines of the innominate bones, pubic crests and the upper border of the symphysis pubis. The abdomen is largely enclosed by muscles, its shape and size varying with the degrees of distension of the contained hollow organs and the phases of respiration. Muscular tone is a large factor in maintaining the positions of the abdominal and pelvic viscera (pp. 826, 832).

Abdomen proper. This is bounded: **in front** by the rectus abdominis muscles, the pyramidales and the aponeurotic parts of the obliqui externus, internus and transversus abdominis; **laterally** by the fleshy parts of these flat muscles, the iliacus muscles and iliac bones, **behind** by the lumbar vertebral column, diaphragmatic crura, paired psoas and quadratus lumborum muscles and the posterior parts of the iliac bones; **above** by the diaphragm, while **below** it is continuous with the lesser pelvis through its superior aperture (p. 670). Since the diaphragm, the domed roof of the abdominal cavity, is convex upwards, part of the cavity lies within the skeletal framework of the thorax (pp. 815–816). The abdomen proper contains most of the digestive tube, liver, pancreas, spleen, kidneys, ureters (in part), suprarenal glands and numerous blood and lymph vessels, lymph nodes and nerves.

Lesser pelvis. Approximately funnel-shaped, like an inverted, truncated cone, this region extends postero-inferiorly from the abdominal cavity proper (**12**.73, 74) and is bounded: **anterolaterally** by the innominate (hip) bones below their pubic crests and arcuate lines, and by the obturatores interni; **posterosuperiorly** by the sacrum, coccyx, piriformes and coccygei; **inferiorly** by the levatores ani which, with their covering fasciae, form the pelvic diaphragm (p. 829), and by the transversi perinei profundi and sphincter urethrae which, with **their** fascial coverings, constitute the urogenital diaphragm. The lesser pelvis contains: the urinary bladder, terminal parts of the ureters, the sigmoid colon, rectum, some ileal coils, internal genitalia, blood and lymph vessels, lymph nodes and nerves.

The abdominal and pelvic muscles are ensheathed in fascia, which receives regional names from adjacent structures, e.g. on the internal surface of transversus abdominis is the *transversalis fascia* (p. 829), inferior to the diaphragm is the *diaphragmatic fascia*, covering the psoas and iliacus is the *iliac fascia* (p. 870); anterior to the quadratus lumborum is the *anterior layer of the thoracolumbar fascia* (p. 809) and over the muscles in the pelvis is the *pelvic fascia* (p. 830). Most abdominal and pelvic organs are largely covered by a serous membrane, the *visceral peritoneum* (pp. 1734–1746) whereas the walls of the abdomen are lined by *parietal peritoneum*.

Abdominal regions

For the location of viscera in clinical practice, the abdomen is divided into nine regions by imaginary planes, two horizontal and two parasagittal, their edges indicated by lines projected to the surface of the body (**12**.70). The upper, horizontal, *transpyloric plane* (of Addison) is indicated by a line encircling the body midway between the suprasternal notch and the symphysis pubis (or midway between the umbilicus and inferior end of the sternal *body* or a hand's breadth below the xiphisternal joint); it intersects the first lumbar vertebral body near its lower border and meets the costal margins at the tips of the ninth costal cartilages. The lower horizontal, *transtubercular plane* corresponds to a line round the trunk level with the iliac tubercles (**12**.70, p. 671); it cuts the front of the fifth lumbar vertebral body near its upper border. The abdomen is thus divided into three arbitrary zones; each is further subdivided into three by the *right* and *left lateral planes*, indicated on the surface by vertical lines through points midway between the anterior superior iliac spines and the symphysis pubis (these lines are also called 'mid-clavicular' or 'mammary' lines).

The median upper *epigastric* is flanked by *right* and *left hypochondriac* regions; the median region of the middle zone is the *umbilical* region, flanked by *right* and *left lumbar*, or *lateral*, regions. The lower median *hypogastric* or *pubic* region is between the *right* and *left iliac* or *inguinal regions* (**12**.70) (see Addison 1899–1901). A third horizontal plane, often used in abdominal topography, the *subcostal plane*, corresponds to a line level with the lowest limits of the tenth costal cartilages. It cuts the front of the third lumbar vertebral body nears its upper border. It often replaces the transpyloric plane in descriptions of abdominal regions.

The *umbilicus* is variable in position, being usually level with the disc between the third and fourth lumbar vertebrae in young adults but, as age advances and in conditions of deficient abdominal tone, it sinks lower. It is also lower in children because of the underdeveloped condition of the pelvic region.

On the body's posterior surface a transverse line between the highest points on the iliac crests and level with the fourth lumbar vertebral spinous process delineates a *supracristal plane*. The fourth spine is a useful landmark in identifying other vertebral spinous processes. After removal of the anterior abdominal wall (**12**.70), the viscera are partly displayed as follows: above and right is the liver, largely in the shelter of the lower right ribs and cartilages, extending across the midline, where it descends to the transpyloric plane. The stomach is partly exposed in the angle between the left costal margin and the lower hepatic border; from its lower border an apron-like peritoneal fold, the *greater omentum*, descends for a varying distance anterior to the other viscera. Below this, however, some coils of the small intestine are usually visible. In the right iliac region the caecum

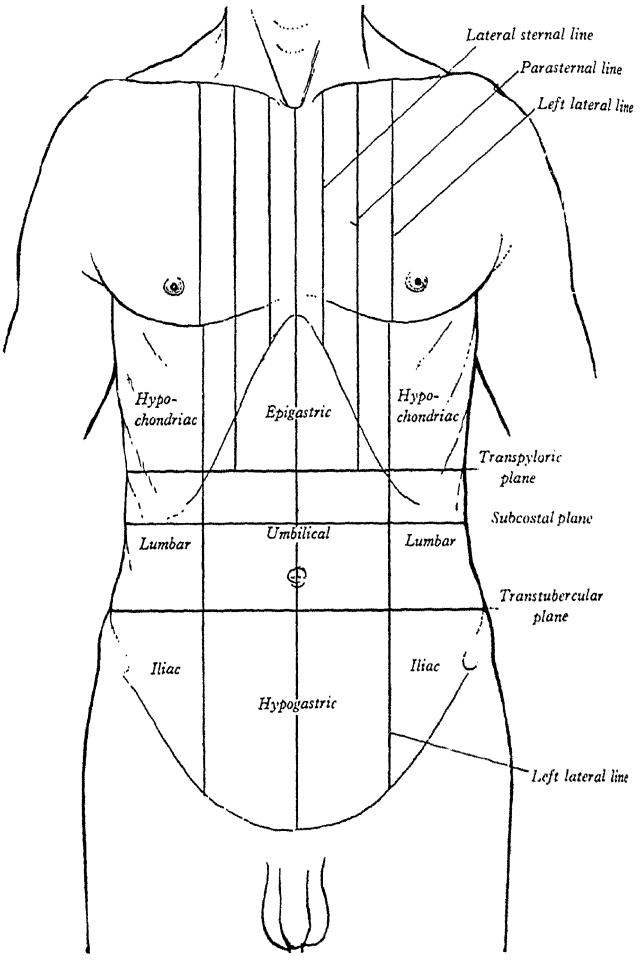
and, in the left iliac region, the lower part of the descending colon are partly exposed (p. 1777). The urinary bladder, in the anterior part of the pelvis, ascends above the symphysis pubis into the hypogastric region when distended; the rectum is in the sacral concavity, usually hidden by coils of the small intestine. The sigmoid colon may appear between the rectum and the bladder.

Followed to the right, the stomach is continuous with the *duodenum*, their junction being marked by a thick, palpable *pyloric sphincter*. The duodenum reaches the liver and curves down under its cover. If, however, the great omentum and the transverse colon behind it are turned up over the chest, the horizontal part of the duodenum can be seen crossing the vertebral column from right to left. The duodenum then ascends to the second lumbar vertebra to become continuous with the coils of the *jejunum* and *ileum*, which are about 6 metres long (p. 1765) and form the rest of the small intestine. Followed inferiorly, the ileum ends in the right iliac region, opening into the colon at the junction of the *caecum* and *ascending colon*. From the caecum the colon ascends on the right, then loops to the left across the median plane below the liver and stomach and turns downwards; thus it is composed of *ascending, transverse* and *descending* parts. In the pelvis it forms a loop, the *sigmoid colon*, ending in the rectum. The *spleen* is posterolateral to the stomach in the left hypochondriac region and is partly exposed by displacing the stomach to the right.

The sheen on the surfaces of the abdominal wall and exposed viscera is due to their covering of *peritoneum*, a serous membrane.

The relations of the organs described here obtain in the recumbent position, but visceral relations depend on posture, respiratory movements and the degree of distension of the hollow organs. The shapes of chest, abdomen and pelvis also vary, as do organs in the same individual and at different times, depending on physiological activity and mobility. Therefore the surface outlines of viscera, particularly the hollow organs described here, must be regarded as highly variable within wide limits.

In physique, individuals have been classified into two extremes: *hypersthenic* (pyknic) and *asthenic* (leptosomatic) with intermediate grades, *sthenic* and *hyposthenic* (Mills 1917, 1922). In the hypersthenic, with massive physique, the thorax is wide and short and the subcostal angle very obtuse, so that the heart and lungs are wide transversely; the abdomen is widest superiorly and the stomach less elongated vertically, with the pylorus relatively high; while the transverse colon is more truly transverse. In the asthenic type, with a light and slender physique, the thorax is long and narrow and the subcostal angle acute, so that the heart and lungs are long and narrow; the abdomen is widest inferiorly, the stomach being long with a relatively low pylorus and the colon long with a V-shaped transverse colon descending to the pelvis. Varieties of physique (somatotypes) have also been classified as endomorphic (massive), mesomorphic (intermediate) and ectomorphic (slender) with intermediate grades, each reputed to have predominant psychological characteristics (Sheldon et al 1940; Sheldon & Stevens 1942; see current physical anthropology monographs for details).



12.70 Reference lines on the anterior aspect of the thorax and abdomen for use in delineating surface projections.

PERITONEUM (12.72–81)

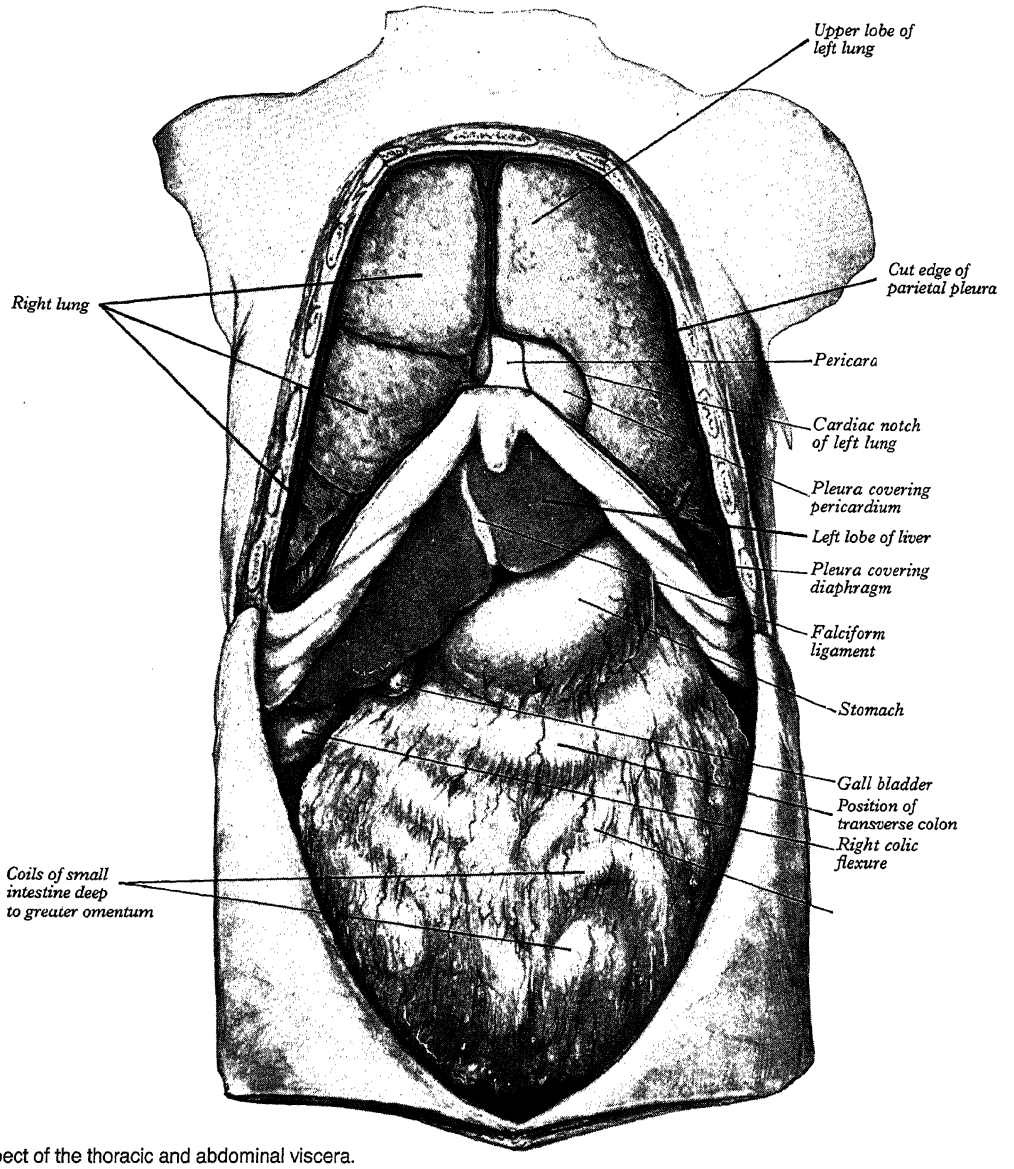
The peritoneum (Brizon et al 1956), the largest and most complexly arranged of the serous membranes, is an empty and intricately folded sac, lining the abdomen and reflected over the viscera. In males it is a closed sac; in females the lateral ends of the uterine tubes open into the sac's potential cavity. Where it lines the abdominal wall (parieties) it is named the *parietal* peritoneum and is reflected over the viscera as the *visceral* peritoneum. Its free surface is covered by a layer of *mesothelium*, kept moist and smooth by a film of serous fluid. Hence mobile viscera glide freely on the abdominal wall and each other within limits dictated by their attachments. Sessile organs are covered by peritoneum wherever they are in contact with mobile viscera.

The peritoneal cavity is a *coelom* (p. 192)—a discontinuity in the mesoderm lined by an epithelium-like single layer of cells (mesothelium) which maintains the surface. Loss of this mesothelium leads to the adherence of underlying tissues and interference with visceral function, which may be serious and even lethal (p. 1745), providing convincing evidence of an essential function of the serosa, the separation of the viscera sufficiently for unimpeded activity.

Many functions are served by coelomic spaces in invertebrates and vertebrates (Jones 1913; Romer 1970). Excretory organs such as nephridia drain fluid and excretory products from a general coelom, and vertebrate nephric systems are partly derived from it. As animals evolved to greater size, a coiled gut became essential but such coiling could not evolve and develop without the emergence of a coelom. In some lower vertebrates the gametes are extruded from the gonads into a coelom in both sexes, persisting in the females of more advanced forms, including mankind. Special ducts have evolved to connect the kidneys and testes to the cloaca (and its derivatives) and are in part formed from coelomic epithelium, which is also involved in formation of the gonads themselves (p. 199).

GENERAL STRUCTURE

A considerable amount of *extraperitoneal connective tissue* separates the parietal peritoneum from the muscular strata of the abdominal walls, blending with their fascial lining. Its thickness and content of fat vary in different regions. While parietal peritoneum is generally attached only loosely by this tissue to the abdominal and pelvic walls and so is easily stripped from them, the tissue is denser on the inferior surface of the diaphragm and behind the linea alba, the parietal peritoneum being here more firmly adherent. Its attachment is especially loose in some places, allowing the alteration in size of certain organs; e.g. in the pelvis and the adjoining anterior abdominal wall it allows the urinary bladder to distend upwards behind the



12.71 Anterior aspect of the thoracic and abdominal viscera.

wall, from which it temporarily strips the peritoneum as it ascends. There is usually much perinephric extraperitoneal fat on the posterior abdominal wall. The visceral peritoneum, in contrast, is firmly united to the underlying tissues and cannot be easily detached; its connective tissue layer (*tela subserosa*) is continuous with the fibrous matrix of the visceral wall; and the visceral peritoneum must therefore be considered as part of its viscus, a concept of significance in pathology.

PERITONEAL CAVITY

The parietal and visceral layers of peritoneum are in sliding contact, the potential space between them being the *peritoneal cavity*. This consists of:

- a main region, the *greater sac*
- a diverticulum, the *omental bursa* or *lesser sac* behind the stomach and adjoining structures.

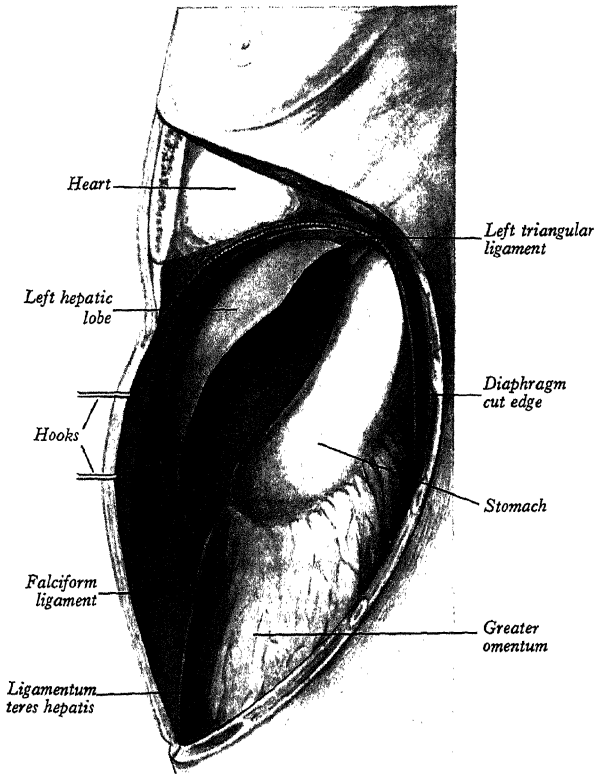
The two communicate via the *epiploic foramen (aditus to the lesser sac)*.

The complex arrangement of the peritoneum can best be rationalized by the study of alimentary development (pp. 181–186) and by examination in cadavers before they are made unnaturally rigid by preservative fluids. To trace the peritoneum from one viscus to another and from viscera to parieties, it is useful to follow its continuity in vertical and horizontal directions and simpler to describe the greater and lesser sacs separately.

VERTICAL DISPOSITION OF THE PERITONEUM

The ensuing descriptions will be more clearly comprehended by making frequent reference to the development of the alimentary tract (pp. 181–186) and to the illustrations in this section.

It is convenient to commence tracing the arrangement of the greater sac in the vertical plane (**12.75**) from the anterior abdominal wall at the umbilical level. A fibrous *ligamentum teres (obliterated left umbilical vein*, p. 1502) ascends from this point to the inferior surface of the liver. It inclines slightly to the right, and recedes from the anterior abdominal wall as it ascends, to raise a triangular *falciform ligament of the liver (***12.72**, 139); this is composed of two layers of parietal peritoneum (right and left) with connective tissue between, continuous with the anterior body wall in front, and the inferior surface of the diaphragm above. This develops from the most ventral part of the embryonic mesogastrium. The falciform ligament has right and left peritoneal layers with intervening connective tissue (**12.77**A, B). Its juxta-umbilical region has a posterior free border from the umbilicus to the inferior hepatic surface,



12.72 Dissection to expose the left side of the falciform fold or ligament of the liver.

containing the *ligamentum teres*. Superiorly the falciform ligament extends from the diaphragm to become continuous with the visceral peritoneum on the anterosuperior surface of the liver (**12.72**). At the site of reflexion from the diaphragm to the liver, the two layers diverge (**12.113**, 139–141), the right passing transversely to the right as the *superior layer of the hepatic coronary ligament* (from the diaphragm to the upper surface of the right hepatic lobe), the left layer passing left as the *anterior layer of the left hepatic triangular ligament* (from the diaphragm to the upper surface of the left hepatic lobe).

The visceral peritoneum on the anterosuperior surface of the liver continues down and round the sharp inferior hepatic border to the inferior (visceral) surface, where it is arranged as follows: right of the gallbladder it covers the inferior surface of the right lobe of the liver and is reflected posteriorly to the right suprarenal gland and the upper pole of the right kidney, forming the *inferior layer of the coronary ligament*; it often passes direct from the liver to the kidney as the *hepatorenal ligament*. From the right kidney it descends to the front of the first part of the duodenum and right colic flexure; it also passes medially in front of a short segment of the inferior vena cava (between the duodenum and liver), continuing on to the posterior wall of the omental bursa (**12.75**, 76). Between the two layers of the coronary ligament is a large, triangular, posterior area on the right hepatic lobe devoid of peritoneal covering, the *bare area of the liver*, where the liver is attached to the diaphragm by loose connective tissue.

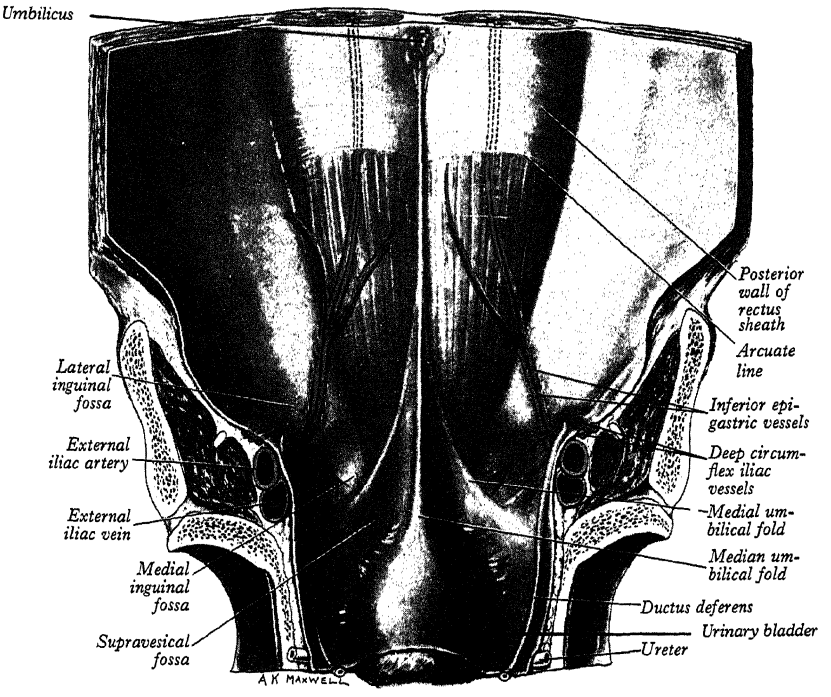
Near the right hepatic margin, layers of the coronary ligament converge, fusing to form the *right triangular ligament* which connects the right hepatic lobe to the diaphragm (**12.76**, 139, 140) and forms the apex of the bare area, the base being the *groove for the inferior vena cava*.

Visceral peritoneum covers the inferior aspect and sides of the gallbladder, the inferior surfaces of the quadrate lobe of the liver as far back as the anterior margin of the porta hepatis and of the left lobe, from whose posterior surface it reaches the diaphragm as the *posterior layer of the left triangular ligament*. Along the anterior margin of the porta hepatis the peritoneum is continuous at its right end with the peritoneum of the omental bursa, the latter being reflected from the posterior margin of the porta hepatis (**12.140**). The visceral peritoneum plunges into the fissure for the ligamentum venosum, (**12.141**), between the caudate and left hepatic lobes, in two layers, anterior and posterior. The anterior layer merges with peritoneum reflected from the anterior portal margin (**12.140**, 141). From this L-shaped line, formed by the left margin of the fissure for the ligamentum venosum and the anterior margin of the porta hepatis, peritoneum is reflected to the gastric lesser curvature and approximately the first 2 cm of the duodenum, as the *anterior layer of the lesser omentum*.

The region of lesser omentum connecting liver to stomach is the *hepatogastric ligament*, the part passing from the liver to the duodenum being the *hepatoduodenal ligament*. The anterior layer, traced to the right, passes anterior to the hepatic artery, bile duct and portal vein, turning round their right side to continue behind them into the posterior omental layer, which here forms the anterior surface of the bursa. Thus the lesser omentum has a free right border, in which lie the hepatic artery, bile duct and portal vein; behind this border is the *epiploic foramen* (foramen of Winslow) (**12.75**, 77A). The anterior layer of the lesser omentum is continuous below with the visceral peritoneum of the anterior gastric surface and the first 2 cm of the duodenum. This layer then descends from the greater curvature and neighbouring duodenum to become the *most anterior layer of the greater omentum*. Reaching the lower edge of this large fold, it ascends as the greater omentum's *most posterior layer*, running to the anterosuperior aspect of the transverse colon (at the *taenia omentalis*). It then turns back, adherent to but separable from the **upper** layer of the transverse mesocolon, to the anterior aspect of the pancreatic head and the anterior border of the body of the pancreas; it leaves the latter as the upper layer of the transverse mesocolon (**12.75**), passing to the posterior surface of the transverse colon (at the *taenia mesocolica*) and covering all but its posterior aspect, returning thence to the pancreatic head and body as the **inferior** layer of the transverse mesocolon. It then descends over the pancreas to the front of the horizontal and ascending parts of the duodenum, from there turning downwards on the posterior abdominal wall. It is also carried forward on the superior mesenteric vessels to the jejenum and ileum as the *right layer of the mesentery*. It invests them and reaches the posterior abdominal wall as the *left layer of the mesentery*, descending over the abdominal aorta, inferior vena cava, ureters and psoas major muscles into the lesser pelvis. Reflected from the posterior pelvic wall as the *anterior layer of the sigmoid mesocolon*, it encloses the sigmoid colon and returns to the pelvic wall as the *posterior layer* of that mesocolon, descending then to cover the front and sides of the rectum's upper third and the front of its middle third.

In males, the peritoneum leaves the junction of the middle and lower thirds of the rectum, passing forwards to the upper poles of the seminal vesicles and superior aspect of the bladder. Between the rectum and bladder it forms the *rectovesical pouch*, descending slightly below the upper seminal poles to a level about 7.5 cm from the anal orifice. From the apex of the bladder it returns along the median and medial umbilical ligaments (**12.73**) to the anterior abdominal wall and umbilicus. When the bladder distends, the peritoneum is lifted from the lower anterior abdominal wall so that part of the bladder's anterior surface is in **direct** contact with the wall (p. 1838). Instruments can then be passed through the wall into the bladder without traversing the peritoneum.

In females, the peritoneum passes from the rectum to the posterior vaginal fornix and then to the back of the uterine cervix and body, as the *recto-uterine fold*, which descends to form the *recto-uterine pouch* (of Douglas), the base of which is only 5.5 cm from the anal orifice. The peritoneum spreads over the uterine fundus to its anterior (vesical) surface as far as the junction of the body and cervix, from which it is reflected forwards to the upper surface of the bladder, forming a shallow *vesico-uterine pouch*. Peritoneum on the anterior and posterior uterine surfaces leaves the organ to reach the lateral pelvic walls as the *broad ligaments of the uterus*, each consisting of antero-inferior and posterosuperior layers continuous at the upper border of the ligament; between them at this border is the uterine tube. Behind the broad ligament a double fold of peritoneum passes back to the ovary and blends with its covering (see p. 1869). Peritoneum is reflected from the bladder to the anterior abdominal wall as in males.



12.73 The infra-umbilical part of the anterior abdominal wall of a male subject: posterior surface, with the peritoneum in situ. Note the pelvic bones flanking the wide greater pelvis (middle) and narrower lesser pelvis (below) containing the bladder.

HORIZONTAL DISPOSITION OF THE PERITONEUM

Below the transverse colon the arrangement is simple, but differs at pelvic, lower abdominal and upper abdominal levels.

In the lesser pelvis

The peritoneum follows the surfaces of the pelvic viscera and walls, with differences in the sexes. **In males** (**12.73**, 74) it almost encircles the sigmoid colon, passing to the posterior pelvic wall as the *sigmoid mesocolon*. It leaves the sides and finally the front of the rectum, continuing over the upper poles of the seminal vesicles to the bladder; lateral to the rectum it forms right and left *pararectal fossae*, varying with rectal distension, and anteriorly a *rectovesical pouch*, limited laterally by peritoneal folds reading from the sides of the bladder posteriorly to the anterior aspect of the sacrum, the *sacrogenital folds*, each lateral to its pararectal fossa. Anteriorly peritoneum covers the superior surface of the bladder, forming on each side *a paravesical fossa*, limited laterally by a ridge containing the ductus deferens. The size of these fossae depends on the state of the bladder; when it is empty, a variable *transverse vesical* fold bisects each fossa, and the anterior ends of the sacrogenital folds may sometimes be joined by a ridge separating a *middle fossa* from the main rectovesical pouch (**12.73**). Between the paravesical and pararectal fossae the only elevations are due to the ureters and internal iliac vessels.

In females, pararectal and paravesical fossae also appear, the lateral limit of the latter being the peritoneum investing the round ligament of the uterus. The rectovesical pouch is, of course, divided by the uterus and vagina into a small, anterior, vesico-uterine and a deep, posterior, recto-uterine pouch (**14.15**). Marginal recto-uterine folds of the latter correspond to the sacrogenital folds in males and pass back to the sacrum from the sides of the cervix lateral to the rectum. The *broad ligaments* extend from the sides of the uterus to the lateral pelvic walls, with the uterine tubes contained in their free superior margins and the ovaries attached to their posterior layers. Below, they are continuous with the lateral pelvic parietal peritoneum. Between the elevations over the obliterated umbilical artery and the ureter on the lateral pelvic wall is a shallow *ovarian fossa* containing the ovary in nulliparous females. It lies behind the lateral attachment of the broad ligament.

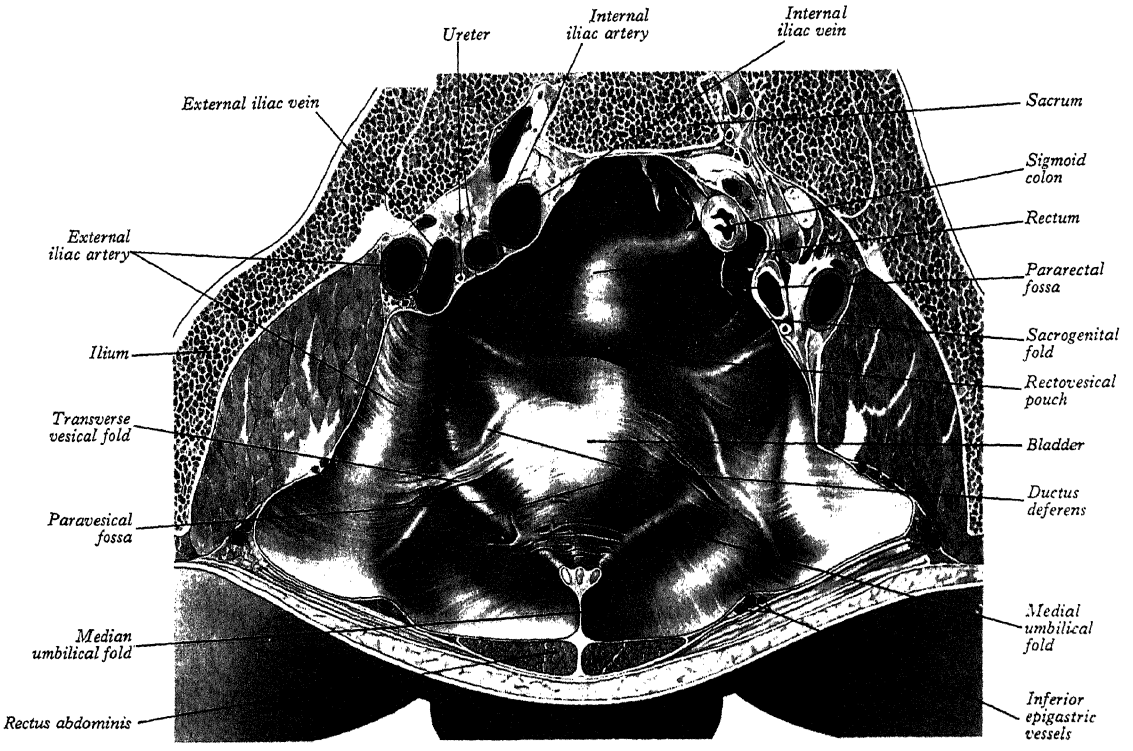
In the lower abdomen

The peritoneum of the lower anterior abdominal wall is raised into five ridges converging upwards (**12.73**). A *median umbilical fold* extends from the apex of the bladder to the umbilicus. It contains the urachus (p. 1838). On each side of it the obliterated umbilical artery raises a *medial umbilical fold*, ascending from pelvis to umbilicus. Between these three folds are the two *supravesical fossae*. Further laterally each inferior epigastric artery raises a *lateral umbilical fold*, below its entry into the rectus sheath. *Medial inguinal fossae* exist between the lateral and medial umbilical folds. A *lateral inguinal fossa* over the deep inguinal ring is lateral to the lateral umbilical fold and indicates the site of descent of the processus vaginalis and testis into the anterior abdominal wall. A *femoral fossa*, inferomedial to the lateral inguinal and separated from it by the medial end of the inguinal ligament, overlies the femoral ring (p. 1564).

From the linea alba, caudal to the level of the transverse colon, the peritoneum, followed horizontally to the right, lines the abdominal wall almost to the lateral border of quadratus lumborum; it is reflected over the sides and front of the ascending colon, enclosing the caecum and vermiform appendix and passing medially over the duodenum, psoas major and inferior vena cava towards the median plane, whence it passes along the superior mesenteric vessels to invest the small intestine and back again to the large vessels anterior to the vertebral column, forming the *mesentery* (**12.75**, 76). This encloses: the jejunum, the ileum, superior mesenteric blood vessels, nerves, lacteals and lymph nodes. The peritoneum then continues left across the abdominal aorta and left psoas major, covering the sides and front of the descending colon, and then returns round the abdominal wall to the midline.

In the upper abdomen (12.75, 76, 77A, 88, 89)

Above the transverse colon, the arrangement of the peritoneum in the greater sac is more complex. From the front of the inferior vena cava, just above the first part of the duodenum, it passes **left** behind the epiploic foramen to form the posterior wall of the omental bursa (**12.77A**); it passes **right** over the front of the right suprarenal gland and the upper pole of the right kidney to the anterolateral abdominal wall. From the anterior median line a double fold, the *falciform ligament*, passes back to the right around the liver. To the left the



12.74 The peritoneum of the male pelvis: anterosuperior view. The median umbilical fold contains both the unpaired median and the paired medial umbilical ligaments in the plane of section in this subject.

peritoneum lines the anterolateral abdominal wall, covers the lateral part of the left kidney and passes to the splenic hilum as the posterior (lateral) layer of the *splenicorenal* (lienorenal) or *phrenicolienal ligament* (**12.77A**). It then invests the spleen, returning to the front of its hilum and thence to the cardiac end of the greater curvature as the left layer of the *gastrosplenic ligament*. Covering the anterosuperior gastric surface and adjacent duodenum, it ascends from the lesser curvature to the liver as the anterior layer of the lesser omentum, whose right free border has been described (p. 1736); this anterior layer of the lesser omentum (peritoneum of the greater sac) continues as the posterior layer of the omental bursa (peritoneum of the omental bursa).

OMENTAL BURSA (LESSER SAC)

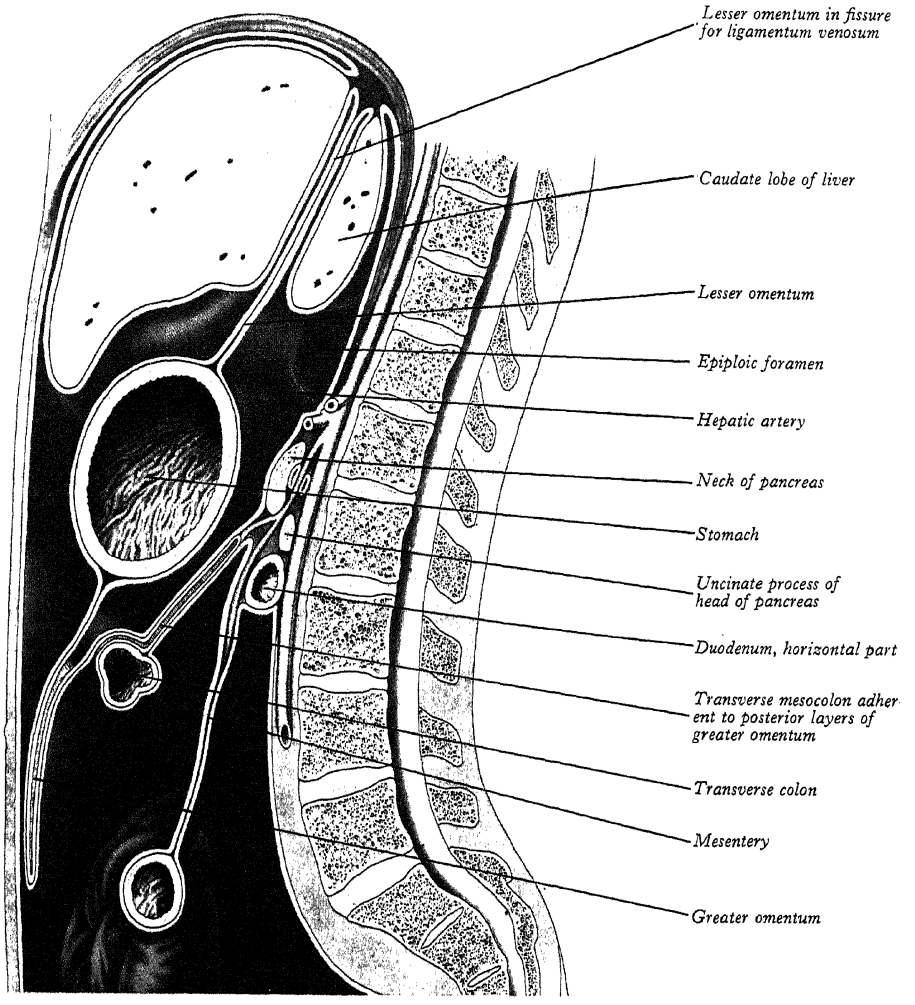
The omental bursa or lesser sac is a large, irregular, potential recess behind the stomach and beyond its limits. Its name is related to the concept that it forms a bursa (p. 781) facilitating movements of the posterior aspect of the stomach. However, it is not closed; its connection with the greater sac is narrowed by embryological rather than functional factors. The stomach expands or contracts just as freely in vertebrates with no special narrow-necked diverticulum. (In any case movements of the *anterior aspect* of the stomach also occur.) The extensive anterior and posterior walls of the 'bursa' are limited by variable borders (right, left, inferior and superior). It is separated from the greater sac except at its upper *right border* where they communicate by a vertical slit, the *epiploic foramen*. Its upper posterior wall is a single peritoneal layer closely applied to the posterior abdominal wall (**12.75**) but below the pancreas its potential cavity projects into the greater omentum, whose posterior wall is formed by two layers which, above the transverse colon, blend with the transverse mesocolon (**12.75**). The greater omentum is traditionally described as having **four** peritoneal layers; but it must be understood that the mesothelial peritoneum is lost, except where a true surface persists. Where two separate 'folds' of peritoneum adhere and blend, the opposed mesothelia disappear but recognizable layers of subepithelial connective tissue often remain.

Epiploic foramen

The epiploic foramen (foramen of Winslow, aditus to the lesser sac) is a short, vertical slit of about 3 cm, leading from the upper part of the right border of the lesser sac into the greater sac, this border forming the foramen's *anterior margin* and containing between its layers the bile duct (on the right), portal vein (posterior) and hepatic artery (left) (**12.77A**). Superiorly the two layers separate, the posterior covering the caudate process of the liver in the *roof* of the foramen (**12.78**) and descending anterior to the inferior vena cava as the foramen's *posterior margin*. At the upper border of the first duodenal segment this layer passes forwards from the inferior vena cava, above the head of the pancreas, into the posterior layer of the lesser omentum, forming the foramen's *floor* which is medially continued down into the right border of the lesser sac (**12.87**). Passing forwards below the medial end of this floor the hepatic artery passes between the two layers of the lesser omentum (**12.77A**). A narrow passage, the *vestibule* of the omental bursa, is left of the foramen between the caudate process and the first part of the duodenum. To the right the rim of the foramen is continuous with the peritoneum of the greater sac: the roof is continuous with the peritoneum on the inferior surface of the right hepatic lobe (**12.139–141**); the posterior wall with the peritoneum on the right suprarenal gland (**12.88**); its anterior wall with the anterior layer of the lesser omentum round the portal vein and bile duct (**12.77A**), the floor with the peritoneum on the lower part of the right suprarenal gland and on adjacent parts of the duodenum and right kidney. Anterior and posterior walls of the foramen are normally apposed.

Omental bursa

The omental bursa has an anterior wall formed by three peritoneal components which are continuous with each other, as follows: (1) peritoneum over the postero-inferior aspect of the stomach and about the first 2 cm of the duodenum; this layer descends to become the posterior of the anterior two layers of (2) the greater omentum, and then ascends to the right to leave the lesser gastric curvature and duodenum at its upper border, becoming (3) the posterior layer



12.75 Sagittal section through the abdomen, approximately in the median plane. Compare with **12.76**. The section cuts the posterior abdominal wall along the line YY in **12.76**. The peritoneum is shown in blue except along its cut edges, which are left white.

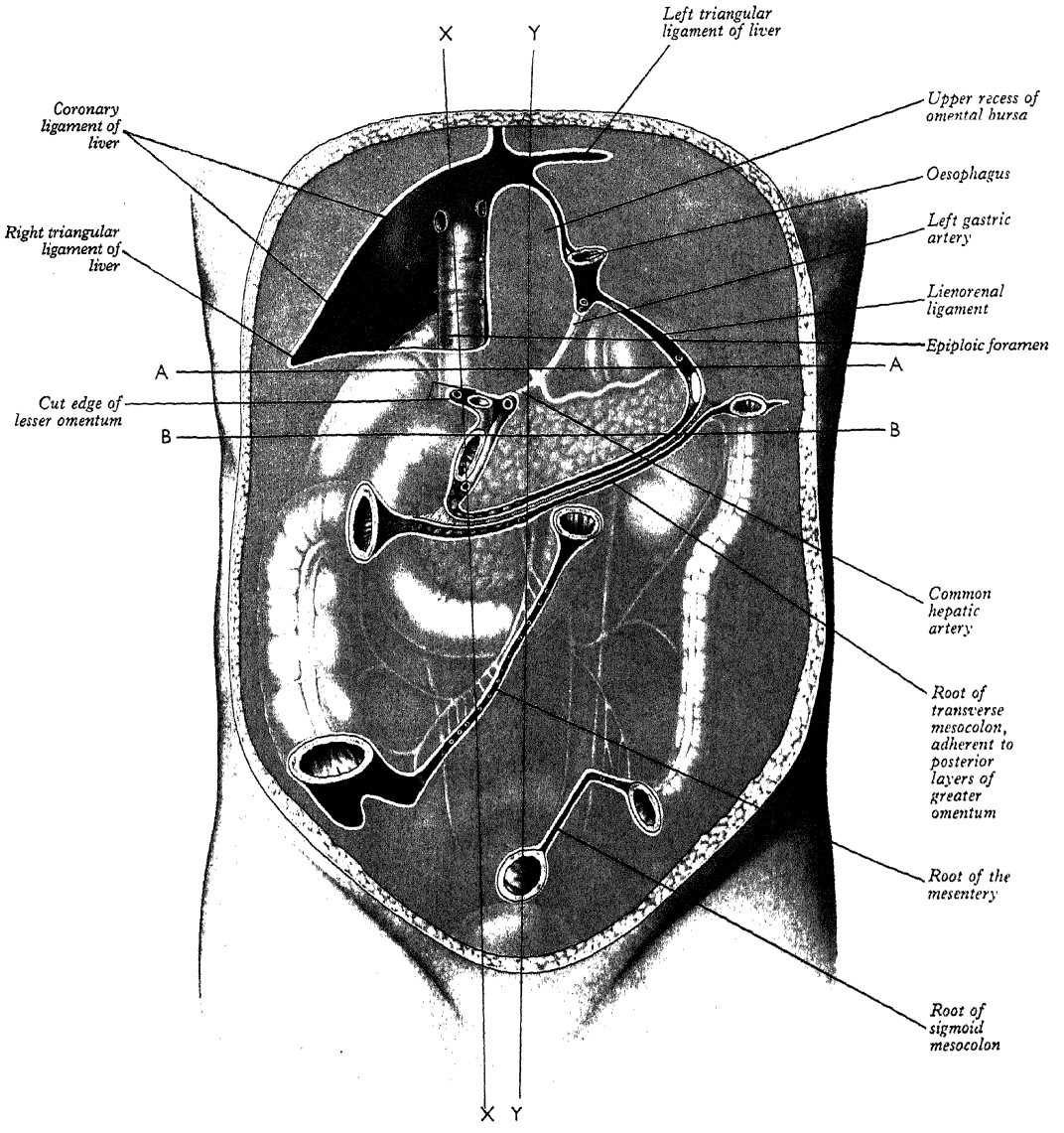
of the lesser omentum. The bursa is often described as ascending behind the caudate lobe, but this projects into the bursa from its right border and is covered by peritoneum on both anterior and posterior surfaces (**12.75**, 139–141).

The *posterior wall* is formed by the anterior of two posterior layers of the greater omentum. Above, the posterior of these is fused, but not inseparably, with the upper peritoneum of the transverse colon and mesocolon. Surgical separation of the greater omentum from these provides posterior access to the stomach through the posterior wall of the greater omentum. Dissection where the omentum and transverse colon meet opens up an embryological 'bloodless plane' between vessels of the greater omentum (from the gastro-epiploic) and the middle colic vessels in the transverse mesocolon (Freder 1905; Lardennois & Okinczyc 1913; Grégoire 1922; Ogilvie 1935). There are no anastomoses across this plane. Above the anterior pancreatic border the posterior bursal peritoneum covers the posterior abdominal wall, a small part of the head and the whole neck and body of the pancreas, part of the anterior aspect of the left kidney, most of the left suprarenal gland, the commencement of the abdominal aorta and coeliac artery and part of the diaphragm. The inferior phrenic, splenic, left gastric and hepatic arteries lie partly behind the bursa (**12.75–77A**, 96).

The *limits of the bursa* are the lines where its posterior peritoneal wall is reflected to be continuous with its anterior; their positions vary somewhat. The *inferior border* is, developmentally (p. 185), the lower limit of the greater omentum; but partial fusion of the latter's layers usually occurs after birth, so that the bursa's *cavity* in adults does not usually extend very far below the transverse colon. The internally apposed peritoneal surfaces lose their mesothelium. The narrow *upper border* is between the right side of the oesophagus and the upper end of the fissure for the ligamentum venosum (**12.141**). Here peritoneum of the posterior omental wall is reflected anteriorly from the diaphragm to join the posterior layer of the lesser omentum.

The *right border* corresponds, below, to that of the greater omentum; above, its upper part is formed by reflexion of the peritoneum from the pancreatic neck and head on to the inferior aspect of the beginning of the duodenum; the line of this reflexion ascends to the left, along the medial side of the gastroduodenal artery. Near the upper duodenal margin the right border joins the floor of the epiploic foramen round the hepatic artery proper (**12.76**). Above this interruption the border is formed by the reflexion of peritoneum from the diaphragm to the right margin of the liver's caudate lobe and along the left side of the inferior vena cava (**12.76**).

The *left border* again corresponds, below, to that of the greater omentum. Above the root of the transverse mesocolon (**12.76**) the border broadens and is formed by the *splenico- (lieno-) renal* and *gastrosplenic ligaments* (**12.77A**), both formed from a part of the original dorsal mesogastrium (p. 183). The splenicorenal ligament extends from the front of the left kidney to the splenic hilum as a bilaminar fold, enclosing the splenic vessels and pancreatic tail (**12.76**, 77A). From the hilum these two layers proceed to the greater curvature of the stomach as the gastrosplenic ligament. The inner (right) layer of the splenicorenal ligament joins the corresponding layer of the gastrosplenic; but its outer (left) layer joins the peritoneum covering the spleen at the back of the hilum. The latter is reflected from the front of the hilum, as the outer (left) layer of the



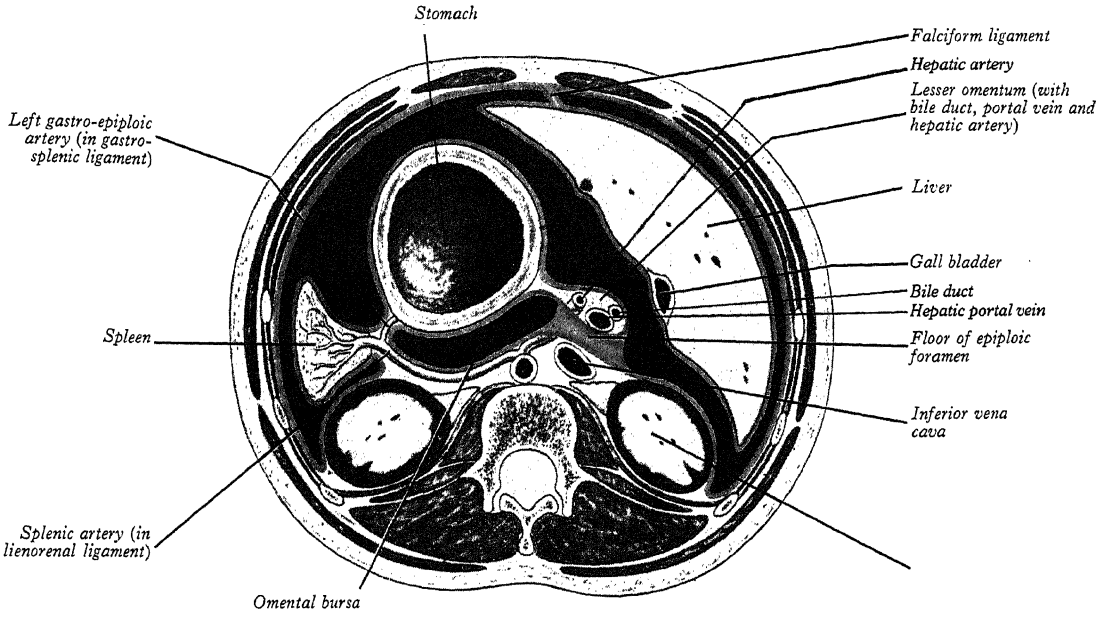
12.76 The posterior abdominal wall, showing the lines of peritoneal reflexion, after removal of the liver, spleen, stomach, jejunum, ileum, caecum, transverse colon and sigmoid colon. The various sessile (retroperitoneal) organs are seen shining through the posterior parietal peritoneum. Note: the ascending and descending colon, duodenum, kidneys, suprarenals, pancreas and inferior vena cava. Line YY represents the plane of **12.75**. Line AA represents the plane of **12.77A**. Line XX represents the plane of **12.77B**.

gastrosplenic ligament. The spleen thus projects left into the greater sac (**12.77A**). The part of the bursa projecting towards it, between the splenic ligaments, is the *splenic recess*. Superiorly the two ligaments merge into a short *gastrophrenic ligament*, passing forwards from the diaphragm to the posterior aspect of the fundus of the stomach. Its two layers diverge near the oesophagus, leaving part of the posterior gastric surface devoid of peritoneum. The upper end of the left border is continuous with the left end of the roof; the left gastric artery turns forwards here into the lesser omentum. (Many peritoneal **folds** are misleadingly termed 'ligaments'. With little in common in structure or function with skeletal ligaments, they are more often neurovascular pedicles of organs which **must** be covered by peritoneum. Some may have a supportive function, but the evidence for this is usually tenuous.)

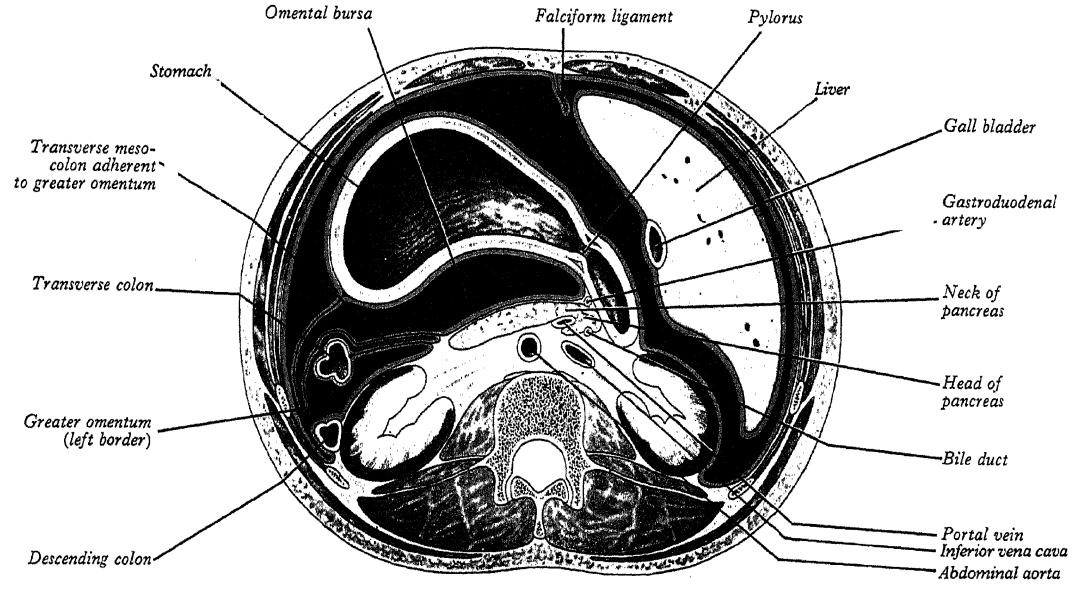
The omental bursa is narrowed by two crescentic peritoneal folds drawn into the lesser sac by the hepatic and left gastric arteries. The *left gastropancreatic fold* transmits the left gastric artery from the posterior abdominal wall to the lesser curvature of the stomach; the *right gastropancreatic fold*, at a lower level, transmits the hepatic artery from the posterior abdominal wall to the lesser omentum (**12.76**). The folds vary much in size, but when well marked they constrict the lesser sac to form a *foramen bursae omenti majoris*. The *superior recess* of the omental bursa is above this constriction, communicating through it to the *inferior recess* (representing the embryonic pancreatico-enteric recess, p. 183). The superior recess thus lies posterior to the lesser omentum and liver, the inferior behind the stomach and in the fold of the greater omentum.

During much of fetal life the transverse colon is attached to the posterior abdominal wall by its own mesentery, the posterior two layers of the greater omentum passing in front of the colon, a condition which may persist (see **12.75**); usually, however, the mesentery of the transverse colon and posterior omental layer adhere; even so, these layers are separable in adults, especially in the living (pp. 1742, 1743), though their mesothelial elements disappear where the layers have fused. In its final form the omental bursa separates the stomach from structures which form the 'stomach bed' (p. 1757) and therefore facilitates movements of the stomach over these structures.

Peritoneal folds between various organs, or connecting them to the abdominal and pelvic walls, enclose the vessels and nerves



12.77A Transverse section through the abdomen, at the level of line AA in **12.76**, viewed from above. The peritoneal cavity is shown in dark blue; the peritoneum and its cut edges in lighter blue.



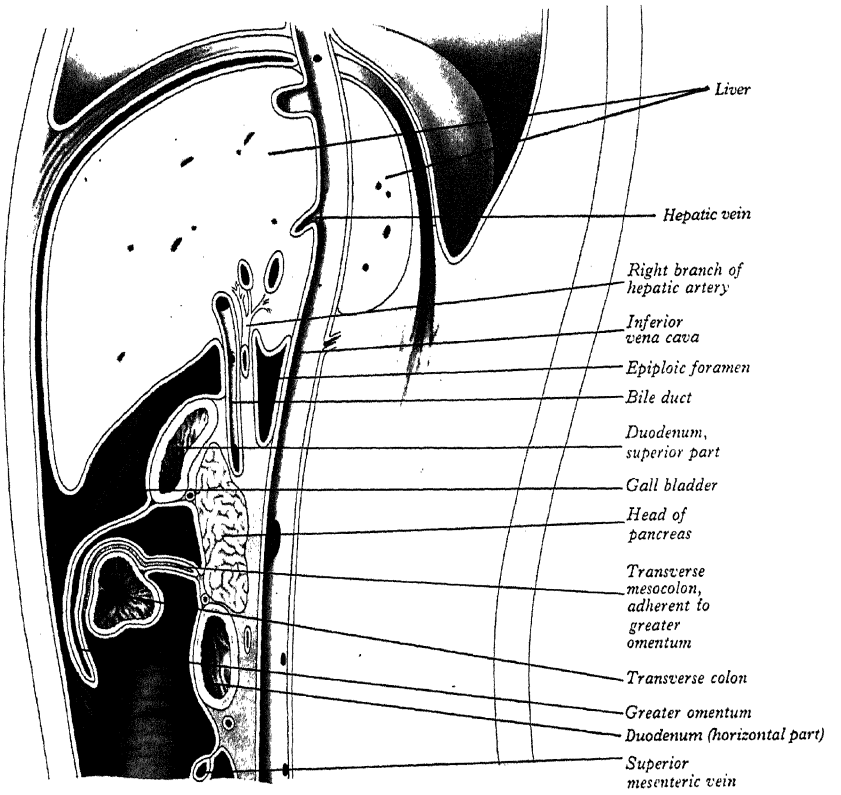
12.77B Transverse section through the abdomen at the level of the line BB in **12.76**, viewed from above. Colours as in **12.77A**.

proceeding to the viscera; though clearly not designed to sustain much weight, they may help to retain certain viscera in contact with each other. They are named ligaments, omenta and mesenteries. (The inappropriate nature of the term 'ligament' has been alluded to above.) An 'omentum' is a cover; the word may have been used to denote an apron and is thus suitable for the greater omentum, but is less suitably extended to other gastric peritoneal folds. The peritoneal 'ligaments' will be described with their respective organs.

OMENTA

Lesser omentum

The lesser omentum is the fold of peritoneum that extends to the liver from the lesser gastric curvature and the commencement of the duodenum; it develops from the embryonic ventral mesogastrium (p. 183). It is continuous with the two layers covering the antero-superior and postero-inferior gastric surfaces and about the first 2 cm of the duodenum. From the lower part of the lesser curvature and upper border of the duodenum these two layers ascend as a double fold to the porta hepatis; from the upper part of the lesser curvature they pass to the bed of the fissure for the ligamentum venosum. This hepatic attachment is J-shaped, with a hook-like limb corresponding to the margins of the porta hepatis and a vertical ascending along the roof of the fissure (**12.**140, 141), at the superior limit of which the lesser omentum reaches the diaphragm where its two layers separate around the abdominal part of the oesophagus. At the right omental border the two layers are continuous and this free margin is anterior to the epiploic foramen. (The omentum may be described as consisting of *hepatogastric ligament* between the liver and stomach, and a *hepatoduodenal ligament* between the liver and duodenum, although these are continuous and essentially form a single entity.) Close to its right free margin the two omental layers enclose the hepatic artery, portal vein and bile duct, a few lymph



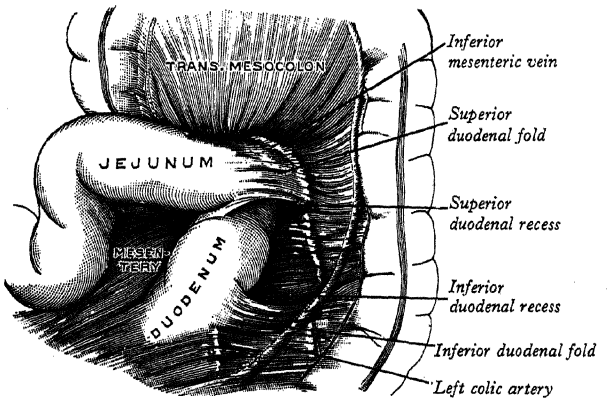
12.78 Section through the upper part of the abdominal cavity, along the line XX in (**12.76**). The boundaries of the epiploic foramen are shown and a small recess of the omental bursa is displayed in front of the head of the pancreas. Note that the tranverse colon and its mesocolon are adherent to the posterior two layers of the greater omentum.

nodes and lymph vessels and the hepatic plexus of nerves, all ensheathed in a *perivascular fibrous capsule* (**12.77**A). The right and left gastric vessels, branches of the gastric (vagus) nerves (p. 1253), and some of the left gastric lymph nodes and their lymph vessels are all contained between the two layers near their gastric attachment. The lesser omentum is thinner on the left and may be fenestrated. This variation in thickness is dependent upon the amount of connective tissue, especially fat.

Greater omentum

The greater omentum, the largest of the peritoneal folds (**12.71**, 72, 75, 78), is a double sheet, folded on itself to make four layers. The anterior double-layered fold descends from the greater curvature of the stomach and first part of the duodenum in front of the succeeding part of the small intestine for a variable distance and ascends behind itself as far as the transverse colon (opposite the taenia omentalis). It adheres to, though it is separable from, the peritoneum on the superior surface of the transverse colon and mesocolon (p. 1740). The left border is continuous above with the gastrosplenic ligament; the right border extends to the commencement of the duodenum. (It must be emphasized that the greater omentum and gastrosplenic ligament are not merely continuous but the same structure, separated only by descriptive convenience and terminology. Their continuity has been further obscured by **changes** in terminology; the gastrosplenic *ligament* was formerly an *omentum* but is now officially the gastro-*lienal* ligament (an inadvisable use of the stem 'lien', the spleen, in a region where all else is 'splenic'!). The greater omentum is usually thin and cribriform but it always contains some adipose tissue, which in the obese may be massive in amount. Between the two layers of its anterior fold, close to the greater curvature of the stomach, the right and left gastro-epiploic vessels form a wide anastomotic arc. Variations in distribution and anastomoses of arteries in the omentum were recorded by Jiang Dian-fu.

Apart from storing fat, the greater omentum may limit peritoneal infection. When the abdomen is opened without disturbance it is frequently found wrapped about the organs in the upper abdomen; it is rarely evenly dependent anterior to the intestines. It is less absorptive than the general peritoneum. It may be congenitally absent and may be removed without apparent ill effect and is hence not physiologically vital. It contains numerous fixed macrophages which are easily mobilized. These may accumulate into dense, oval or round visible '*milky-spots*'. Similar spots may occur on other serous membranes (pleura p. 1662), pericardium and sometimes the leptomeninges.



12.79 The superior and inferior duodenal recesses. The transverse colon and jejunum have been displaced (after Jonnesco, from Poirier & Charpy *Traité d'Anatomie humaine*. Masson et Cie).

MESENTERIES

Peritoneal folds, designated mesenteries, include the mesentery of the small intestine (the mesentery proper), the mesoappendix, transverse mesocolon, sigmoid mesocolon, (sometimes) an ascending or

descending mesocolon and occasionally a mesentery for the gallbladder. They attach these viscera to the posterior body wall, allowing some degree of movement and providing access to vessels and nerves.

Mesentery (of the small intestine)

A broad, fan-shaped fold, it connects the coils of the jejunum and ileum to the posterior abdominal wall. The attached, parietal border is the *root of the mesentery* (**12.76**) about 15 cm (6 in.) long and directed obliquely down from the duodenojejunal flexure (left of the second lumbar vertebra) to the upper part of the right sacro-iliac joint. (Schmidt 1974 measured the mesenteric 'root' in 44 cadavers, finding a mean length of 13.9 cm, with extremes of 7.4 and 19.3 cm.) It passes successively in front of the horizontal part of the duodenum (where the superior mesenteric vessels enter it), the abdominal aorta, inferior vena cava, right ureter and right psoas major. The intestinal border is about 6 m (20 ft) long and compactly plicated. (For variations in length, see p. 1763.) The plication diminishes towards the posterior abdominal wall where the attachment is almost along a straight line. The central part is longest (measured from its root to the intestinal border), attaining a maximum of about 20 cm (8 in.); it shortens towards each end. The mesentery consists of two layers of peritoneum, a right and a left, enclosing the jejunal and ileal branches of the superior mesenteric vessels, with their accompanying neural plexuses, lymph vessels (here called *lacteals*), mesenteric lymph nodes, loose connective and adipose tissue. Fat is most abundant in its lower part and here extends from the root to the intestinal border; the upper mesentery contains less fat, with a tendency to accumulate near the root, leaving rounded, translucent, fat-free areas adjoining the upper jejunum. At the intestinal border, the layers separate to enclose the gut, as its visceral peritoneum. At the mesenteric root the right layer is reflected in its lower part to the posterior abdominal wall and ascending colon and in its upper part to become continuous with the inferior layer of the transverse mesocolon; the left layer passes to the posterior abdominal wall and descending colon. (This arrangement helps to distinguish between the proximal and distal coils of the small intestine when in situ.)

Mesoappendix (12.81)

This is a triangular fold of peritoneum around the vermiform appendix, attached to the back of the lower end of the mesentery close to the ileocaecal junction. It usually reaches the tip of the appendix but sometimes fails to reach the distal third, being then represented by a low peritoneal ridge containing fat. It encloses the blood vessels, nerves and lymph vessels of the vermiform appendix, together with a lymph node (p. 1620).

Transverse mesocolon

A broad fold connecting the transverse colon to the posterior abdominal wall, its two layers pass from the anterior aspect of the head and anterior border of the body of the pancreas to the posterior aspect of the transverse colon (opposite the *taenia mesocolica*), where they separate to surround it. The upper layer is adherent to, but separable from, the greater omentum (pp. 1739, 1740). Posteriorly, the inferior layer covers the inferior aspect of the pancreas and passes in front of the horizontal and ascending parts of the duodenum. Between its layers are the blood vessels, nerves and lymphatics of the transverse colon. The middle colic artery descends to the right, leaving a large avascular area to its left and a smaller one to its right.

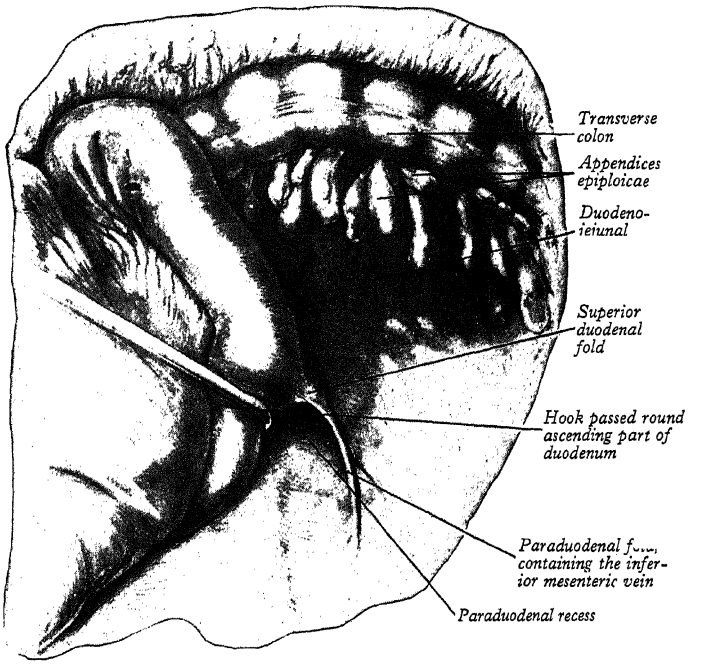
Sigmoid mesocolon

This is a peritoneal fold attaching the sigmoid colon to the pelvic wall, the attachment being an inverted V with an apex near the division of the left common iliac artery (**12.76**); the left limb descends medial to the left psoas major and the right passes into the pelvis to end in the midline at the level of the third sacral vertebra. Sigmoid and superior rectal vessels run between its layers and the left ureter descends into the pelvis behind its apex.

Other mesenteric structures

Peritoneum usually covers only the front and sides of the ascending and descending parts of the colon, but sometimes these are virtually surrounded by peritoneum and attached to the posterior abdominal wall by an ascending and descending mesocolon respectively. The *phrenicocolic ligament* is a peritoneal fold extending from the left colic flexure to the diaphragm level with the tenth and eleventh ribs; it has an anterior edge and passes inferolateral to the lateral end of the spleen, sometimes being misleadingly named the *sustentaculum lienis* or 'splenic shelf', implying a hypothetical supportive role.

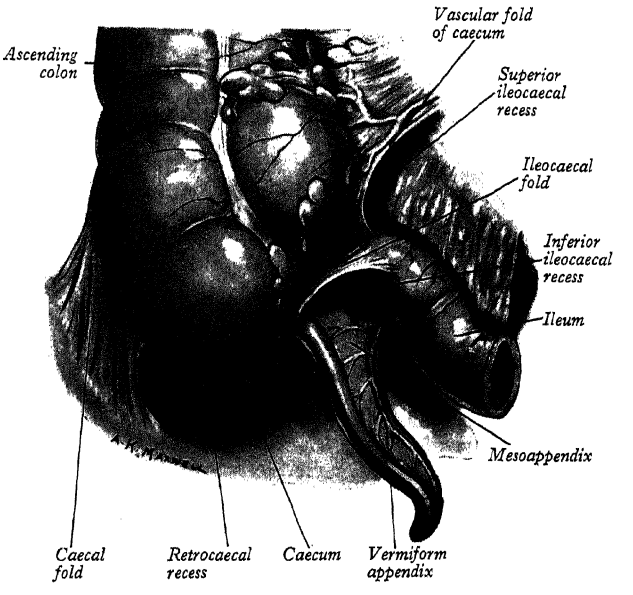
Appendices epiploicae are small peritoneal appendages filled with adipose connective tissue and situated along the colon; they are most conspicuous on the transverse (**12.80**) and sigmoid parts, absent from the rectum and rudimentary on the caecum and appendix. Many contain a small arteriole from the wall of the gut. In the colon they are most numerous along the line of the *taenia libera* (p. 1784).



12.80 The paraduodenal recess.

PERITONEAL RECESSES

Peritoneal folds may create fossae or recesses of the peritoneal cavity.



12.81 The peritoneal folds and recesses in the caecal region.

These are of clinical interest because a segment of intestine may enter one and be constricted by the fold at the entrance to the recess and may be a site of a kind of 'internal' hernia. Since the entrance to a recess may need to be cut to relieve strangulation and to withdraw the gut, the degree of vascularization of the fold becomes important. Surgically the omental bursa belongs to this category, with its opening at the epiploic foramen. Much smaller recesses sometimes occur, sometimes related to the duodenum, caecum and sigmoid mesocolon. For a discussion of the developmental origins of these recesses, see pages 193–194.

Duodenal recesses

Superior duodenal recess (12.79). Present in about 50% of people, this may exist alone but usually occurs with an inferior duodenal recess. It is to the left of the distal end of the duodenum, opposite the second lumbar vertebra, behind a crescentic *superior duodenal fold* (*duodenojejunal fold*), which has a semilunar free lower edge, merging on the left with peritoneum anterior to the left kidney. The inferior mesenteric vein is behind the junction of the left end of this fold and the posterior parietal peritoneum. The recess is about 2 cm deep, admitting a fingertip; it opens downwards, its orifice being in the angle formed by the left renal vein as it crosses the abdominal aorta.

Inferior duodenal recess (12.79). This is present in about 75% of subjects, usually associated with a superior recess with which it may share an orifice; it lies left of the distal end of the duodenum, opposite the third lumbar vertebra, behind a non-vascular, triangular *inferior duodenal fold* (*duodenomesocolic fold*), which has a sharp upper edge. It is about 3 cm deep, admits one or two fingers and opens upwards towards the superior duodenal recess. It sometimes extends behind the ascending part of the duodenum and to the left, in front of the ascending branch of the left colic artery and inferior mesenteric vein. This large fossa is liable to become the site of an internal hernia.

Paraduodenal recess (12.80). It may occur with the superior and inferior duodenal recesses. It is more frequent in the fetus and newborn than in adults, in whom it occurs in about 2%. It is a little to the left of the ascending part of the duodenum, behind a falciform *paraduodenal fold*, the free right edge of which contains the inferior mesenteric vein and ascending branch of the left colic artery, the fold being their mesentery. Its free edge lies in front of the wide orifice of the recess, which faces right.

Retroduodenal recess. Rarely present, it is the largest of the duodenal recesses, and lies behind the horizontal and ascending parts of the duodenum in front of the abdominal aorta. It ascends nearly to the duodenojejunal junction, being about 8–10 cm deep and bounded on both sides by *duodenoparietal folds*; its orifice faces down to the left.

Duodenojejunal or mesocolic recess. Present in about 20% and rarely or never accompanied by any other duodenal recess, it is about 3 cm deep and lies on the left side of the abdominal aorta, between the duodenojejunal junction and the root of the transverse mesocolon. Bounded above by the pancreas, on the left by the kidney, and below by the left renal vein, it has a circular opening between two peritoneal folds, which faces down to the right.

Mesentericoparietal recess (of Waldeyer). This is more frequent in the fetus and newborn, occurring in only about 1% of adults. It lies just below the horizontal part of the duodenum, invaginating the upper part of the mesentery towards the right. Its orifice is large and faces left behind a fold of mesentery raised by the superior mesenteric artery.

Caecal recesses

Superior ileocaecal recess (12.81). Usually present and best developed in children, it is often reduced and absent in the aged, especially the obese. It is formed by the *vascular fold of the caecum*, which arches over the anterior caecal artery, supplying the anterior part of the ileocaecal junction, and its accompanying vein. It is a narrow slit bounded in front by the vascular fold, behind by the ileal mesentery, below by the terminal ileum and on the right by the ileocaecal junction. Its orifice opens downwards to the left.

Inferior ileocaecal recess (12.81) It is well marked in youth but frequently obliterated by fat in later years. It is produced by the *ileocaecal fold*, extending from the antero-inferior aspect of the terminal ileum to the front of the mesoappendix (or to the appendix or caecum). It is also known as the '*bloodless fold of Treves*', although it sometimes contains blood vessels; if inflamed, especially when the appendix and its mesentery are retrocaecal, it may be mistaken for the mesoappendix. (For the source of vessels in this fold, see Cabanie & Javelle 1966.) The recess is bounded in front by the ileocaecal fold, above by the posterior ileal surface and its mesentery, to the right by the caecum, and behind by the upper mesoappendix. Its orifice opens downwards to the left.

Retrocaecal recess (12.81). Behind the caecum, it varies in size and extent and ascends behind the ascending colon, being large enough to admit an entire finger. It is bounded in front by the caecum (and sometimes the lower ascending colon), behind by the parietal peritoneum and on each side by *caecal folds* (parietocolic folds) passing from the caecum to the posterior abdominal wall. The vermiform appendix frequently occupies this recess (pp. 1775–1776).

Intersigmoid recess

This recess is constant in fetal life and infancy, but may later disappear. It lies behind the apex of the V-shaped parietal attachment of the sigmoid mesocolon, is funnel-shaped and directed upwards and opens downwards. It varies in size from a dimple to a fossa admitting the fifth finger. Its posterior wall of posterior parietal peritoneum covers the left ureter as this crosses the bifurcation of the left common iliac artery. Occasionally the recess is within the layers of the sigmoid mesocolon nearer the gut than its root. Its presence is due to an imperfect blending of the mesocolon with the posterior parietal peritoneum.

ANOMALOUS PERITONEAL FOLDS

Certain other folds, bands or ligaments sometimes occur in the abdomen. Some are considered to cause obstruction by pulling on or kinking sections of intestine; others may limit the spread of peritoneal effusions. Their exact modes of origin are doubtful; they have been attributed to errors in development, previous inflammation (peritonitis), mechanical traction by the gut and even (and improbably) linked with the evolution of upright posture. These anomalous folds must be distinguished from pathological adhesions definitely due to peritonitis; also, when coils of intestine are pulled out of normal position during examination they may be artificially kinked, with resultant simulation of bands. Anomalous folds are only clinically important if proved to interfere with normal function; their presence should not halt a search for other possible causes of the symptoms. The commonest anomalous folds encountered are as follows:

- Occasionally the lesser omentum is prolonged to the right of the usual site of the epiploic foramen by a peritoneal fold extending from the gallbladder to the superior part of the duodenum (*cystoduodenal ligament*), or in front of the superior part of the duodenum to the greater omentum or right colic flexure, or from the inferior surface of the right hepatic lobe to the right colic flexure (*hepatocolic ligament*).
- The duodenojejunal junction is sometimes joined to the transverse mesocolon by a peritoneal band.
- The greater omentum may be attached to the front of the ascending colon or extend over it to the lateral abdominal wall. A thin sheet of peritoneum (*Jackson's membrane*), containing small blood vessels, may spread from the front of the ascending colon and caecum to the posterolateral abdominal wall and may merge on the left with the greater omentum. Occasionally a band passes from the right side of the ascending colon to the lateral abdominal wall near the level of the iliac crest. Sometimes termed a 'sustentaculum hepatis', it is closely related to the liver only in fetal and early postnatal life, when the liver is relatively larger. Other folds between the ascending colon and posterolateral abdominal wall may divide the right lateral paracolic gutter (between the ascending colon and posterior abdominal wall) into several small recesses.
- The ascending and less frequently the descending colon may have a mesentery.

- Proximal and distal ends of the sigmoid colon may be tied together by a fibrous band.
- Frequently a fan-shaped *presplenic fold* extends from the front of the gastrosplenic ligament (near the greater gastric curvature), below the inferolateral pole of the spleen, to blend with the phrenicocolic ligament; it may adhere to the spleen or diaphragm and contain rami of the splenic or the left gastro-epiploic artery; the omental bursa may enter it. It is more obvious in the fetus, often appearing as just part of the phrenicocolic ligament in adults. It may limit peritoneal effusions in the left supracolic space (see below), and, if adherent to the spleen or diaphragm, it may form a vascular obstruction in splenectomy.
- A fibrous band, described as passing from the terminal ileum to the posterior abdominal wall, and a similar one from the proximal sigmoid colon to the same wall, were once thought to be causes of partial obstruction by kinking of these parts of the gut, but this view is no longer popular.

SPECIAL PERITONEAL REGIONS

Regarding the spread of pathological collections of fluid, certain potential peritoneal spaces or recesses, normally in communication with each other, must be mentioned because they may be sealed off by pathological adhesions. These are as follows:

Supracolic space (subphrenic region). Between the diaphragm and the transverse colon and mesocolon, it is subdivided into the following:

Right subphrenic space. This is between the diaphragm and the anterior, superior and right lateral surfaces of the right lobe of the liver, bounded on the left side by the falciform ligament and behind by the coronary ligament's upper layer.

Left subphrenic space. Between the diaphragm, the anterior and superior surfaces of the left hepatic lobe, the anterosuperior surface of the stomach and the diaphragmatic surface of the spleen, it is limited to the right by the falciform ligament and behind by the left triangular ligament's anterior layer.

Right subhepatic space (hepatorenal recess, or Morison's pouch). Bounded above and in front by the inferior surface of the right hepatic lobe and gallbladder, below and behind by the right suprarenal gland, the upper part of the right kidney, the descending part of the duodenum, right colic flexure, transverse mesocolon and part of the head of the pancreas, above and behind, it extends between the right kidney and the liver as far as the inferior layer of the coronary ligament and right triangular ligament.

Left subhepatic space. i.e. the omental bursa.

Right infracolic space. This lies postero-inferior to the transverse colon and mesocolon and to the right of the mesentery, whose obliquity narrows the lower part of the space. The vermiform appendix is often in the lower part of this space.

Left infracolic space. This is below and behind the transverse colon and mesocolon and left of the mesentery; it is widest below, continuing into the pelvis.

Pelvic cavity. (See p. 829.)

Paracolic gutters. These are alongside the ascending and descending colon (which are normally sessile), where the peritoneum turns dorsally on the medial and lateral aspects of the gut. *Medial* and *lateral paracolic gutters* flank both left and right parts of the colon. Of commonest clinical interest is the *right lateral paracolic gutter*, which skirts the superolateral aspect of the hepatic flexure of the colon and continues into the hepatorenal pouch (of Morison) and, through the epiploic foramen, into the omental bursa and its superior recess. Inferiorly, around the caecum it curves over the pelvic brim into the *rectovesical pouch* (male) or *recto-uterine pouch* of Douglas (female). Related to this gutter, and its superior extension, are the vermiform appendix, right kidney, gallbladder, lesser gastric curvature and the first and second parts of the duodenum; all are common sites of acute abdominal disease. Seepage of infected fluid along this channel, from place to place, may cause puzzling symptoms and signs and errors in diagnosis. In supine patients infected fluid in the right lateral gutter may **ascend** to, enter and accumulate in the superior recess of the omental bursa, with grave consequences, because of its inaccessibility and nearness to the pleural and pericardial cavities. In patients nursed in a sitting posture, fluid **descends** to the relatively accessible rectovesical pouch or to the recto-uterine pouch, approachable surgically through the rectum or vagina.

Two extraperitoneal subphrenic regions. These may become infected:

- the *right extraperitoneal space*, between the two layers of the coronary ligament, i.e. the 'bare area' of the liver and the diaphragm
- the *left extraperitoneal space*, which contains extraperitoneal connective tissue around the left suprarenal gland and upper pole of left kidney.

PERITONEAL MICROSTRUCTURE

The peritoneum is composed of a single layer of flat mesothelial cells lying on a layer of loose connective tissue. The mesothelium usually forms a continuous surface, adjacent cells being joined by junctional complexes but probably allowing the passage of macrophages, just as leucocytes pass between endothelial cell junctions. In some areas, e.g. the greater omentum, the peritoneum may be discontinuous, having fenestrations which are sometimes visible to the unaided eye; but mesothelium continues over the trabeculae of connective tissue interlacing around such fenestrae.

Submesothelial connective tissue contains cells typical of loose connective tissue (p. 75) but macrophages, lymphocytes and in some regions adipocytes are particularly numerous. Macrophages and lymphocytes may aggregate as submesothelial 'milky spots'. Mesothelial cells may also transform into fibroblasts; the fusion between layers of fibroblasts of mesothelial origin may cause macroscopic adhesions between the peritoneal surfaces, interfering with intestinal motility or even leading to complete obstruction of the gut.

The mesothelium resembles vascular endothelium in being a dialysing membrane which fluids and small molecules may traverse. Numerous endocytic vesicles occur near the cell surfaces, the remaining cytoplasm being poor in organelles, indicating low metabolic activity (Tesi & Forssmann 1970). Normally the volumes of fluid transmitted by peritoneal surfaces are small, but large volumes may be administered via the intraperitoneal route; conversely, substances such as urea can be dialysed from blood into fluid circulated through the peritoneal cavity.

PERITONEAL FLUID

The fluid covering the peritoneal surfaces contains water, electrolytes and other solutes derived from interstitial fluid in the adjacent tissues and from the plasma of local vessels. It also contains proteins and cells (Carr 1967), the latter varying in number, structure and type in different diseases; hence it is of diagnostic importance. Normally they are mesothelial desquamated elements, nomadic peritoneal macrophages, mast cells, fibroblasts, lymphocytes and some other leucocytes. Some, particularly macrophages, migrate freely between the peritoneal cavity and the surrounding connective tissue; intraperitoneally injected particles are ingested by them and transported to various tissue sites. Lymphocytes provide both cellular and humoral immunological defence mechanisms.

Absorption

Substances in **solution** are probably absorbed into the capillaries, whereas suspended matter is thought to pass into the lymph vessels, aided by macrophages. After abdominal or pelvic operations, it has been customary to prop up patients to encourage intraperitoneal effusions to gravitate into the pelvis. One reason for this was the belief that the subphrenic peritoneum was more absorptive than elsewhere and hence inflammatory products would enter the circulation more rapidly here. It was supposed that gaps or (peritoneal stomata) between the mesothelial cells of the subphrenic peritoneum and similar gaps (endothelial stigmata) between the endothelial cells of lymph vessels greatly facilitated absorption. Such gaps have been often considered to be histological artefacts, but scanning electron microscopy supports the existence of slit-like orifices. However, absorption is believed to be much the same in all parts of the peritoneum. Greater absorption in the upper abdomen may be due to the larger subphrenic peritoneal area and to respiratory movements.

PERITONEAL VESSELS AND NERVES

The parietal and visceral peritoneum are developed from, respectively, the somatopleural and splanchnopleural layers of lateral plate mesoderm (p. 155). Parietal peritoneum is therefore supplied by somatic blood vessels of the abdominal and pelvic walls; its lymphatics join those in the body wall and drain to parietal lymph nodes; its nerve supply is derived from nerves supplying the muscles and skin of the parietes. Visceral peritoneum, however, as an integral part of the viscera, derives its blood vessels from those supplying viscera. Its lymphatics join the visceral vessels and its nerve supply is autonomic or visceral afferent. Differences in the sensibility of the two layers correlate with their innervations. Whereas pain is elicited by mechanical, thermal or chemical stimulation of the parietal peritoneum, the visceral peritoneum and viscera are not affected; e.g. the liver, stomach or intestine can be injured without evoking pain, insensibility extending from the mid-oesophagus to the junction of endoderm and ectoderm in the anal canal. However, tension *does* evoke pain when applied to viscera or visceral peritoneum by overdistension or traction on mesenteries, stretching various neural elements in the visceral walls or mesenteries. Also effective are spasms of visceral muscle and ischaemia. Somatic nerves of the parietal peritoneum also supply the corresponding segmental areas of skin and muscles and, when the parietal peritoneum is irritated, muscles are reflexly contracted, causing rigidity of the abdominal wall. The parietal peritoneum on the underside of the diaphragm is supplied with afferent fibres centrally by the phrenic nerves and peripherally by the lower six intercostal and subcostal nerves. Hence peripheral irritation may result in pain, tenderness and muscular rigidity in the distribution of the lower thoracic spinal nerves, while central irritation may result in pain in the cutaneous distribution of the third to fifth cervical spinal nerves, i.e. the shoulder region.

Clinical examination of the abdomen is nothing more than an exercise in applied anatomy. As each part of the abdomen is viewed or felt, the underlying anatomical structures must be in the mind's eye of the observer. The subject is placed supine with a single pillow behind the head and shoulders. Systematic examination comprises the classical quartet of inspection, palpation, percussion and auscultation.

Inspection

Inspection reveals useful information about the build of the subject. The superficial fatty layer of the abdomen is normally 1 to 2 cm in thickness. This is reduced to millimetres in the cachectic and increased to 5 or more centimetres in the obese. The umbilicus is normally situated half way between the tip of the xiphoid process and the top of the symphysis pubis. It is displaced upwards by swellings which arise in the pelvis, for example the pregnant uterus, and displaced downwards in gross obesity and ascites.

When the muscles of the anterior abdominal wall are contracted by raising the head and shoulders from the couch, the midline linea alba and the linea semilunaris on either side can be seen, demarcating the rectus abdominis muscle. In a well-built subject, the transverse ridges of its muscle intersections can also be seen.

Palpation

Palpation is performed using the flat of the hand, the palpating agent being the flexor surfaces of the fingers used collectively. Relaxation of the abdomen is vital so the subject is reassured and asked to breathe quietly through the mouth. The pulsations of the aorta can be felt in the midline by firm pressure on the anterior abdominal wall, against the lumbar spine. The aorta terminates in front of the fourth lumbar vertebra. This corresponds with the supracristal plane, which is the line joining the uppermost part of the iliac crest on each side. In the normal subject, this corresponds to a point about 3 cm distal to the umbilicus. In most normal subjects, no other intra-abdominal viscus is palpable and any mass which is detected requires careful further elucidation. However, in healthy, well-relaxed thin subjects, especially female, the following structures may be palpated:

- The lower pole of the right kidney may just be felt on full inspiration by bimanual palpation, in which the fingers of one hand rest on the anterior abdominal wall and the other hand presses firmly forwards in the right flank.
- The lower margin of the liver may be palpable immediately below the right costal margin on full inspiration.
- The sigmoid colon may be felt in the left iliac fossa, particularly if loaded with faeces.

Percussion

The normal abdomen is universally resonant because of the gas-containing gut which lies in front of the solid retroperitoneal organs and the fact that the normal pelvic viscera lie entirely within the true bony pelvis. However, the liver gives a dull note to percussion throughout its extent from the level of the right fifth rib anteriorly to the right costal margin.

Percussion over a palpable mass is useful in determining whether the mass is solid or fluid-filled (dull to percussion) or contains gas (resonant). The clinical presence of free fluid in the abdomen is revealed by dullness in the flanks which moves as the patient rolls from side to side (shifting dullness). However, it requires the presence of a litre or more of fluid before this can be detected by physical examination—more so in the obese subject.

Auscultation

Stethoscopic examination of the normal abdomen reveals low-pitched gurgles of intestinal peristalsis. These sounds are increased, both in volume and in pitch, in organic intestinal obstruction and are absent in paralytic ileus and peritonitis. The presence of a bruit within the abdomen, as elsewhere, signifies turbulent flow in an artery, for example, in a patient with stenosis of the common iliac artery.

It should be noted that examination of the abdomen is not complete without inspection and palpation of the hernial orifices and the external genitalia and examination of the supraclavicular lymph nodes, the last for clinical evidence of metastatic lymphatic spread from intra-abdominal malignant disease.

ALIMENTARY SYSTEM FROM OESOPHAGUS TO ANUS

INTRODUCTION

Despite structural variations along the alimentary tract, there is a common basic plan which is best appreciated by reference to its development (p. 174). Much of the alimentary canal originates as a tube of endoderm enveloped in the splanchnopleuric mesoderm, its external surface facing the intraembryonic coelom. The endodermal lining forms the epithelium of the tract and also the secretory and ductal cells of various glands secreting into the lumen, including the pancreas and liver. The surrounding splanchnopleuric mesoderm

forms the connective tissue, muscle layers, blood vessels and lymphatics of the wall, its external surface becoming visceral mesothelium; this is of course absent throughout the neck and thorax and where the hindgut traverses the pelvic floor. The disposition and development of the dorsal and ventral mesenteries of the subdiaphragmatic foregut and of the dorsal mesentery of the midgut and hindgut are described elsewhere (pp. 186, 188, 191). Associated neural elements invade the gut from neighbouring neural crest tissue (p. 220). Cranially, the skeletal muscle of branchial arch origin and caudally of less certain origin, contribute to the musculature of the gut's extremities. An outline of the alimentary organization is depicted in **12.82**.

GENERAL MICROSTRUCTURE

MATURE GUT WALL (12.82A)

This has a laminated structure in which four main layers (or tunicae) are readily distinguishable; although the layers are firmly attached to each other, the boundaries are clear cut. The innermost layer is the *mucosa* (tunica mucosa, or mucous membrane); this is subdivided into three strata, from inside outwards:

- the lining *epithelium*,
- the *lamina propria*, a layer of loose connective tissue immediately beneath it, where many of the glands are also found,
- the *muscularis mucosae*, a thin layer of smooth muscle.

Beneath the mucosa is the *submucosa* (tunica submucosa), a strong and highly vascularized layer of connective tissue which in some regions also contains glands. External to the submucosa is the *muscularis* (tunica muscularis), also referred to as the *muscularis externa* or muscle coat to distinguish it from the much thinner muscularis mucosae; in most regions this has an inner circular layer and an outer longitudinal, but in the stomach a third, oblique layer is added to the inner surface of the circular layer. Finally, the external surface is bounded by a serosa or adventitia, depending on its position within the body.

Mucosal layers

Epithelium. This is a protective barrier and the site of secretion and absorption (i.e. of selective entry into the body of chemicals derived from the food). The protective function against mechanical (abrasive), thermal and chemical injury is well in evidence in the oesophagus and in the terminal part of the rectum, where the epithelium is thick and stratified, and is covered in mucus which acts as a protective lubricant, as also in the oral cavity and pharynx. Elsewhere in the gut the epithelium is simple, either cuboidal or columnar, and includes cells for absorption and various types of secretory cells. The barrier function and selectivity of absorption is assisted by the presence of tight junctions (p. 27) over the entire epithelium. The amount of secretion and absorption depends on the number of relevant cells present, and on their individual surface areas; these are related to the surface area of the lumen which is increased by the presence of mucosal folds and pits, by crypts, by villi and by glands, while microvilli on the surfaces of individual absorptive cells considerably magnify the area of plasma membranes presented to the contents of the gut. Some glands lie in the lamina propria, some in the submucosa, and some (namely the liver and pancreas) completely outside the wall of the gut. All glands drain into the lumen of the gut through individual ducts. There are also scattered enteroendocrine cells within the epithelial lining.

Lamina propria. Made of compact connective tissue, often rich in elastin fibres, this supports and moulds the shape of the surface epithelium, providing nutrient vessels and lymphatics and immune defence: lymphoid follicles are present in many regions of the gut, including some prominent masses in the appendix, and small intestine (Peyer's patches). It is also the source of various growth factors which regulate cell turnover, differentiation and repair in the overlying epithelium.

Muscularis mucosae. This is well developed in the oesophagus and in the large intestine, especially in the terminal part of the rectum. In spite of its thinness, an inner circular and an outer longitudinal component can usually be distinguished, the latter thicker than the former. In addition, single muscle cells emanating from the muscularis mucosae are found inside the villi or between the columnar glands of the stomach and large intestine. By its contraction, the muscularis mucosae can alter the surface configuration of the mucosa locally, allowing it to adapt to the shapes and mechanical forces imposed by the contents of the lumen, and in the case of intestinal villi, promoting vascular exchange.

Submucosa

The submucosa is the strongest layer of the gut wall, as it contains large bundles of collagen, but it is also pliable and deformable so that it adjusts to changes in length and diameter of the gut. In the oesophagus and rectum the submucosa enters into the folds that project into the lumen; it also enters into the rugae of the gastric wall, and the plicae circulares (valves of Kerkring) of the small intestine, but not into the villi. The submucosa also contains the largest arterial network of the wall, which feeds both the mucosa and the muscle coat.

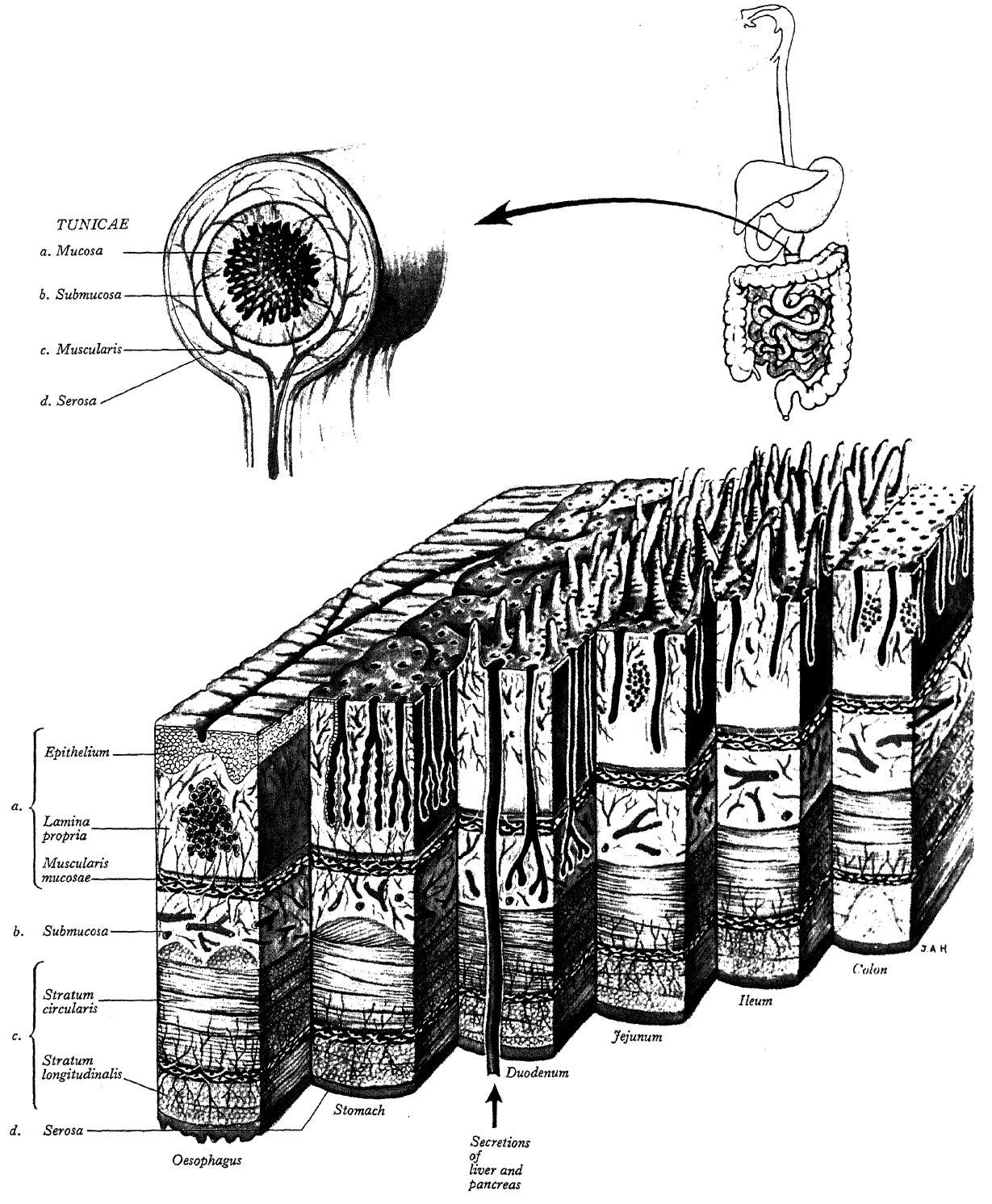
Muscularis externa

This coat usually consists of distinct inner circular and outer longitudinal layers, the antagonistic activities of which create waves of peristalsis responsible for movement of ingested material through the lumen of the gut. In the stomach, where movements are more complex, there is a partial oblique layer, internal to the other two layers. The muscularis externa is chiefly smooth in type, except in the upper oesophagus where skeletal muscle blends with it; here, the musculature resembles that of the pharynx except that it is entirely under involuntary control. For most of its length the smooth muscle of the tract is made of ill-defined bundles of cells, arranged in layers. The smooth muscle cells are typically visceral in type, being somewhat larger than vascular smooth muscle cells; they have a smooth surface, and are about 500 μm long (regardless of body size), and are electrically and mechanically coupled. Their fasciculi lack a perimysium but have sharp boundaries. The layer of circular muscle is invariably thicker than the more external longitudinal coat, except in the colon where the longitudinal muscle is gathered into three cords (taeniae).

Because of the arrangement of the musculature a segment of gut can change extensively not only its diameter (down to a virtual occlusion of the lumen) but also its length; elongation is limited by the insertion of the mesentery. The co-ordinated activity of the two muscle layers and the pattern of activity along the length of the gut produces a characteristic motor behaviour, mainly a propulsive motor activity directed anally (peristalsis) and a non-propulsive motor activity which mixes the luminal contents, as in the stomach, or segments them, e.g. the pyloric sphincter. An important property which bears on the mechanics of the muscle is that it maintains constant volume, so that its shortening is accompanied by an increase in muscle girth. The muscularis externa is traversed by connective tissue septa which pick up the mechanical activity of the muscle, in the manner of minute intramuscular tendons, and discharge it on the submucosa.

Some controversy has existed over the direction of fibres in the layers of the muscularis externa, one suggestion being that the inner circular muscle is a tight helix and the longitudinal one an open spiral (Carey 1921). Other observations (Elsen & Arey 1966) on various mammals, including man, indicated that, despite some deviations from precisely circular and longitudinal directions and some exchange of fasciculi between adjacent circular muscle rings and layers, their fibres do not follow spiral pathways (Schofield 1968).

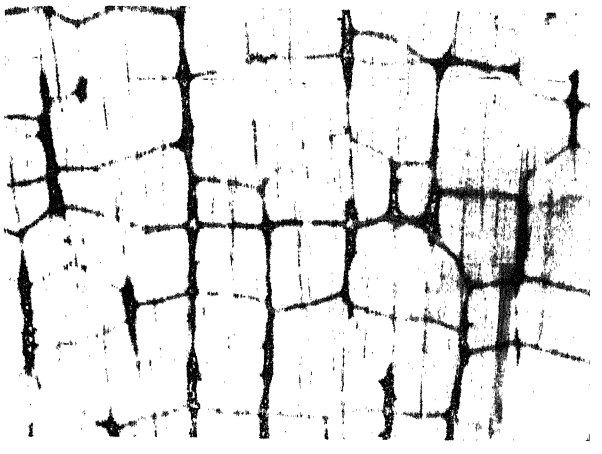
Interstitial cells (of Cajal). Originally described by Ramon y Cajal in 1893, these cells are thin, flat, and somewhat branched, forming strata associated with the enteric neural plexuses and related smooth muscle of the muscularis externa. At the light microscopic level they can be demonstrated with methylene blue staining and Zinc-iodide-osmium impregnation but whether they are muscle or some other (e.g. neural) cell type was a controversy for many years. The recent application of electron microscopy, immunocytochemistry and electrophysiology has to a large degree clarified their nature (see e.g. Berezin et al 1988; Thuneberg 1989; Rumessen 1992; Faussonne-Pellegrini 1992). In general the cells resemble smooth muscle cells in that they contain actin and myosin filaments (Torihashi et al 1993), dense bodies, caveolae and numerous mitochondria, and are linked



12.82A The general arrangement of the alimentary canal, its mural tunicae and (below) the general histology at the levels indicated (highly diagrammatic). The transverse colon (above right) has been displaced downwards to reveal the duodenum.

by gap junctions to typical smooth muscle elements. However there are also differences, for example in the presence of a characteristic flattened, branched smooth endoplasmic reticulum, small ovoid mitochondria and a discontinuous basal lamina, and intermediate filaments of the vimentin type rather than the desmin typical of muscle cells (Torihashi et al 1993). The interstitial cells are in close apposition to the varicose nerve endings of at least two types, one with small (50 nm) round clear vesicles, the other with flat discoidal (70 nm diameter) vesicles (Zhou & Komoro 1992). The neurotransmitters have yet to be identified with certainty, although they may include VIP. Electrophysiology indicates that these cells act as pacemakers for the myogenic contraction of the muscularis externa smooth muscle (Barajas-Lopez et al 1989), and receive modulatory inputs from the enteric nervous system and extrinsic innervation of the gut.

The positions of the interstitial cell strata vary regionally (Faussonne-Pellegrini 1992). In general they lie in the same layers as



12.82B Myenteric plexus in the small intestine, visualised by selective staining in a whole mount preparation, as seen in a micrographic montage. Note the presence of polygonal areas of ganglion cells interconnected by thinner fasciculi. The smooth muscle fibres run transversely in this illustration. Magnification ×200. (Provided by G. Gabella, Department of Anatomy and Embryology, University College, London.)

the enteric plexuses, i.e. in the small intestine close to the myenteric plexus between circular and longitudinal muscle, and between the inner and outer layers of circular smooth muscle (the deep muscle plexus of Schabadasch, see p. 1750). In the oesophagus and stomach they have also been described as scattered among the cells of the circular layer (which is not separated into deep and superficial parts as in the small intestine), and in the large intestine they colocalize with the myenteric plexus and the single layer of the submucosal plexus on the luminal side of the circular component of the muscularis externa. These differences must reflect differing patterns of innervation and muscular activity in the different gut regions, although these remain to be worked out in detail.

Serosa and adventitia

Outside the muscularis externa is a layer of connective tissue of variable thickness, in many places the site of adipose tissue deposition. Where the tract is attached to the body wall by mesentery within the abdominal cavity, i.e. covered in visceral peritoneum, it is lined by *serosa* (serous membrane) consisting of a thin connective tissue layer and an external coat of mesothelium. Elsewhere the connective tissue blends with the surrounding fascial planes of connective tissue and is then termed the *adventitia*. Where the alimentary tract is retroperitoneal (e.g. much of the duodenum) the surface facing the abdominal cavity is lined by serosa, and other parts by adventitia.

Neural and vascular plexuses

Neuronal cell bodies of the enteric nervous system (p. 1310 and see below) are present between the circular and longitudinal components of the muscularis externa (the *myenteric (Auerbach's) plexus*) and in the submucosa (*submucosal (Meissner's) plexus*), providing the intrinsic sensory and motor supply of the gut wall. Extrinsic sensory, motor and sensorimotor nerves from cranial or spinal sources are connected with the enteric nervous system (see below). Vascular plexuses are also present at various levels of the wall especially in the submucosa and mucosa. These plexuses connect with vessels of the surrounding tissues or those entering through the mesentery, and accompany the ducts of outlying glands.

Sources of innervation. The gut is densely innervated by the autonomic nervous system.

Extrinsic innervation. This originates from neurons outside the gut, with functional components from the sympathetic, parasympathetic and visceral sensory divisions of the peripheral nervous system (PNS). Visceral afferent nerves come from sensory ganglion cells situated in the nodose ganglion of the vagus and spinal dorsal root ganglia; parasympathetic efferent neurons originate from the vagal dorsal motor nucleus in the medulla oblongata, and sympathetic efferent neurons arise from the thoracic and lumbar spinal cord, via the prevertebral sympathetic (coeliac, mesenteric and pelvic) ganglia.

Intrinsic innervation. Consisting of neurons located entirely within the gut wall (the intramural ganglionated plexuses), this is so well developed and so complex in its organization that since Langley (1921) it is known as the *enteric nervous system*, a division that is connected with but distinct from, the sympathetic and parasympathetic divisions. Further details are given on p. 1310.

ENTERIC NERVOUS SYSTEM

Introduction

Within the wall of gastrointestinal tract from the oesophagus to anal canal lies a series of ganglionated plexuses. Collectively these form the enteric nervous system, a highly organized neural assemblage with some remarkable features similar to those of the central nervous system (CNS). Because of the intrinsic sensory, motor and interneuronal microcircuitry of the enteric nervous system (ENS) the gut can make complex reflex responses to local stimulation even when, experimentally, all connections to the CNS have been severed. In normal life the ENS governs many activities of the alimentary system, both motor and sensory. It regulates and directs peristaltic contractions of the muscularis externa and movements of the muscularis mucosae, and it governs secretion by mucosal and submucosal glands, local vasoconstriction and vasodilatation, water absorption and electrolyte exchange, and other less well-understood functions including local neuro-immunological and neurotrophic modulations of surrounding tissues. From the vagus and other autonomic nerves the plexuses also receive the preganglionic axons of the parasympathetic system and the postganglionic axons of the sympathetic system which exert external regulatory influences upon the ENS. Sensory information is also relayed to the CNS through visceral afferents, although the relation of these with the ENS is not yet clear. Recent reviews of the ENS have been given by Furness and Costa (1987); see also Hoyle and Burnstock (1989); Timmermans et al (1992); Gershon and Wade (1993).

Locations of enteric plexuses

The cell bodies of the enteric neurons are located in three (or more) ganglionated plexuses situated within the gut wall; they give off numerous axons and other processes which branch and interweave to form non-ganglionated plexuses and ramifications among the surrounding tissues. Ganglia are located at two main levels in the wall thickness, namely:

- within the muscularis externa (the *myenteric ganglionated plexus*) between the circular and longitudinal strata
- the submucosa (two or more *submucosal ganglionated plexuses*).

The non-ganglionated nerve plexuses lie at various levels in the wall, notably in the lamina propria (mucosal plexus), at the interface between the submucosa and muscularis externa (*plexus entericus (submucosus) extremis*), between the circular and longitudinal muscles (the non-ganglionated part of the myenteric plexus), and within the serosa (*serosal plexus*). In the small intestine an extra non-ganglionated plexus lies between the internal and external components of the circular muscle (*plexus entericus profundus*). Fibres, often in groups, also penetrate all tissues of the gut wall including the epithelium.

Ganglion cell types and microcircuitry

The details of ENS microcircuitry have not yet been thoroughly worked out, although recent studies using electrophysiological recording combined with dye injection, immunohistochemistry and lesioning experiments have begun to reveal what appears to be quite a complex and regionally variable organization (see e.g. Furness & Costa 1987; Gershon & Wade 1993). Major species differences in immunohistochemistry also occur even between closely related mammals, making it difficult to draw general conclusions about neurotransmitters and the chemical identities of cell types.

In a classic study with intravital methylene blue staining, Dogiel (1899) distinguished four types of enteric ganglion neurons on the basis of their size and neurite patterns, as follows:

- *Type I cells* are relatively large, with short, stubby irregular paddle-shaped dendrites and a single axon, usually directed orally and therefore perhaps associated with orally-directed peristalsis. They occur only in the myenteric plexus; some of them contain substance P (SP).
- *Type II cells* are smaller with several axon-like processes directed circumferentially and radially. They may represent interneurons or possibly primary sensory cells. They are CGRP-positive in humans, and calbindin positive in guinea pigs.
- *Type III cells* possess a number of branched dendrites and a single axon, often directed anally, and therefore a possible mediator of anally-directed peristaltic waves. They are mostly immunoreactive for 5-HT and calbindin, and some are enkephalin positive. In more recent years Stach (1989) has added to this list other cells with various morphologies.
- *Dendritic (filamentous) Type II cells* which have a number of short as well as long neurites; *Types IV* and *V cells* and *microneurons* (minineurons) which contain various neuromodulatory peptides including vasoactive intestinal polypeptide (VIP), galanin (GAL), substance P (SP) and neuromodulator U (NMU).

The relationships of the different cell types to the large number of known neurotransmitters or neuromodulators (see the list on p. 937) have yet to be satisfactorily worked out. It should however be mentioned that enteric neurons often contain more than one of these chemicals, underlining the functional complexity of the ENS. An interesting recent finding is that some groups of cells are positive for nicotineamide adenine dinucleotide (NADH) diaphorase, identical with nitric oxide synthase, and are therefore probably agents of the nitric oxide-mediated smooth muscle relaxation important in peristalsis and the opening of sphincters. There is evidence that this role is shared with some other neuromodulators including VIP and ATP.

Ganglionated plexuses

For convenience, in this description the transmitter/neuromodulators reported for porcine enteric plexuses by Timmermans et al 1992 will be followed, although as stated above, other species may show different chemicals and chemical combinations.

Myenteric (Auerbach's) plexus (12.82B). This lies between the circular and longitudinal layers of the muscularis externa, consisting of groups of motor neurons and interneurons. It is composed predominantly of Type I cells containing (in pigs) substance P (SP), Type II cells reactive for CGRP and VIP, Type III cells for 5-HT, ENK and calbindin, and microneurons for VIP and GAL (Timmermans et al 1992). The myenteric plexus serves the muscles around it (i.e. the deep part of the circular muscle and the longitudinal layer of the muscularis externa).

Submucosal plexus. This is divisible into a *deep submucosal plexus (of Schabadasch* or of *Henle*: see Hoyle & Burnstock 1989) adjacent to the submucosal surface of the muscularis externa, and a *superficial submucosal plexus* (of *Meissner*) near the submucosal surface of the muscularis mucosae. In the colon other ganglia are present throughout the considerable thickness of the submucosa, and may constitute an additional intermediate plexus, although its cells resemble those of Meissner's plexus in size and immunoreactivity (Hoyle & Burnstock 1989). Neural processes extend from all these ganglia into adjacent structures: the *deep submucosal plexus*.

Deep submucosal plexus. Composed of cells innervating the circular layer of the muscularis externa (among other functions), these contain Type II cells with calcitonin gene-related peptide (CGRP), VIP, SP and DYN, and Type III cells immunoreactive as in the myenteric plexus; microneurons are positive for VIP and GAL.

Superficial submucosal plexus. Supplying the surrounding submucosa, muscularis mucosae, lamina propria and epithelial base, this is thought to contain sensory cells reactive to mucosal stimulation as well as secretomotor neurons and interneurons. Its cells are mainly Type II ganglion cells containing CGRP, SP, GAL and NMU.

Electrical activity of enteric neurons

Electrophysiologically (see e.g. Gershon & Wade 1993), most ganglion cells fall into two categories, designated 1/S and 2/AH types on the basis of their electrical activity (e.g. action potentials of 2/AH cells differ from the 1/S in having a calcium conductance in their falling phase and showing a prolonged after-hyperpolarisation, hence the designation AH). The experimental evidence points to the 2/AH cells being interneurons, at least some of them within the Type II category, with synaptic inputs and, in some cases cholinergic synaptic outputs on to (1/S) motor neurons innervating smooth muscle. Another set of 2/AH-like cells in the submucosal ganglia are thought to be primary sensory neurons with dendrites reaching the base of the epithelium. However, they may only be the second cell in the sensory pathway, as they are stimulated strongly by 5-HT, and the primary receptors may therefore be 5-HT-releasing enteroendocrine cells in the gut epithelium.

The 1/S cells include putative motor neurons, but other functional classes may also show these physiological characteristics. Further research is expected to clarify the relation between the rather simple electrophysiological classification and the undoubtedly complex morphological and functional natures of enteric neurons.

Enteric plexuses and gut motility

Axons from the enteric plexuses pass in various directions: circumferentially around the gut, radially into its different mural layers, and longitudinally into adjacent segments of the alimentary tract. The longitudinal organization is of considerable importance since peristalsis in most of the gut occurs mainly unidirectionally from the oral towards the anal end, and individual peristaltic waves only move for a limited distance along the gut.

Each peristaltic wave of the gut must have an initiation site and as it moves along, must be preceded by a wave of circular muscle relaxation to allow the propulsion of the bolus along the gut. Behind the peristaltic wave the longitudinal muscle is then activated to restore the gut to its resting shape and prepare for the next peristaltic wave. Although visceral smooth muscle is spontaneously contractile, its co-ordination depends on the ENS, coupled with pacemaker activity in specialized smooth muscle cells (see Interstitial cells of Cajal, p. 155) which can spread excitation through gap junctions to many smooth muscle cells. However, other types of motile behaviour can occur; peristalsis in the the ascending and transverse colon, and in the small intestine can undergo reversals of direction during normal alimentation, and static constrictions of circular smooth muscle may also periodically constrict the small and large intestines into segments (segmentation); these activities are thought to promote the mixing of the luminal contents. Movements of these kinds imply a longitudinal and circumferential pattern of co-ordination, involving the organization of smooth muscle cell connectivity, neuronal microcircuitry and appropriate neurochemical control.

In emphasizing the role of the enteric nervous system in these activities one should not, of course, lose sight of the controlling influence of the extrinsic neural connections. As described elsewhere, the cholinergic terminals of parasympathetic fibres act via the enteric plexuses and also directly on smooth muscle to cause increased motility (and secretory activity in the alimentary glands). Postganglionic fibres of the sympathetic system release noradrenalin on to the smooth muscle, causing hyperpolarization and decreased motility. Feedback systems from visceral afferent fibres are involved in the reflex regulation of such effector actions, although the precise routes of peripheral and central nervous interactions accompanying these activities are rather obscure.

Enteric glia. Associated with all layers are enteric glial cells which ensheath neurons and their processes in the same way that Schwann cells do in other parts of the peripheral nervous system (PNS). However, they have some features which mark them as special cells of considerable biological interest because of their similarity to central nervous glial cells. Like the latter cells (and unlike Schwann cells), they contain intermediate filaments composed of glial fibrillary acidic protein (GFAP). Further details are given on p. 939.

Enteric nervous system disease

Much of alimentary pharmacology is concerned directly or indirectly with malfunctions of the enteric nervous system, as affected by microbial infections and other harmful agents which cause increased or decreased gut motility, abnormalities of secretion and other dysfunctions. Apart from the actions of neurotoxins and inflammatory chemicals on the ganglion cells, they can be damaged or killed by invasive organisms, with ensuing alimentary stasis, con-

stipation and various other complications. This is seen, e.g. in Chagas' disease, a tropical infection of the viscera by the flagellate *Trypanosoma cruzi*, and after the prolonged intake of certain chemical substances such as chlorpromazine and senna. The numbers of ganglion cells also diminish in old age, a factor which could contribute to alimentary dysfunction in the elderly (de Souza et al 1993). In Hirschsprung's disease there is a congenital absence of enteric ganglion cells due to embryonic non-migration of neural and glial precursors from the neural crest from which they are derived (p. 220). Typically only part, often only a small sector of the gut, is affected (usually somewhere between the midjejunum and the anal canal, and most often the rectum: see e.g. Kamm 1994). Large defects tend to be fatal during early development or childhood. Biopsies diagnostically show a local absence of ganglion cells from affected regions.

OESOPHAGUS (12.1, 3, 68, 83, 87–89)

The oesophagus is a muscular tube about 25 cm (10 in) long, connecting the pharynx to the stomach. It begins in the neck, level with the lower border of the cricoid cartilage and the sixth cervical vertebra; descending largely anterior to the vertebral column through the superior and posterior mediastina. It traverses the diaphragm, level with the tenth thoracic vertebra, and ends at the gastric cardiac orifice level with the eleventh thoracic vertebra. Generally vertical in its course, it has two shallow curves. At its beginning it is median but inclines to the left as far as the root of the neck, gradually returns to the median plane near the fifth thoracic vertebra, and at the seventh deviates left again, finally turning anterior to traverse the diaphragm at the tenth. The tube also bends in an anteroposterior plane to follow the cervical and thoracic curvatures of the vertebral column. It is the narrowest part of the alimentary tract, except for the vermiform appendix, and is constricted:

- at its commencement, 15 cm (6 in) from the incisor teeth
- where crossed by the aortic arch, 22.5 cm (9 in) from the incisor teeth
- where crossed by the left principal bronchus, 27.5 cm (11 in) from the incisors
- as it traverses the diaphragm, 40 cm (16 in) from the incisors.

These data are important clinically with regard to the passage of instruments along the oesophagus.

Cervical part (12.1, 68)

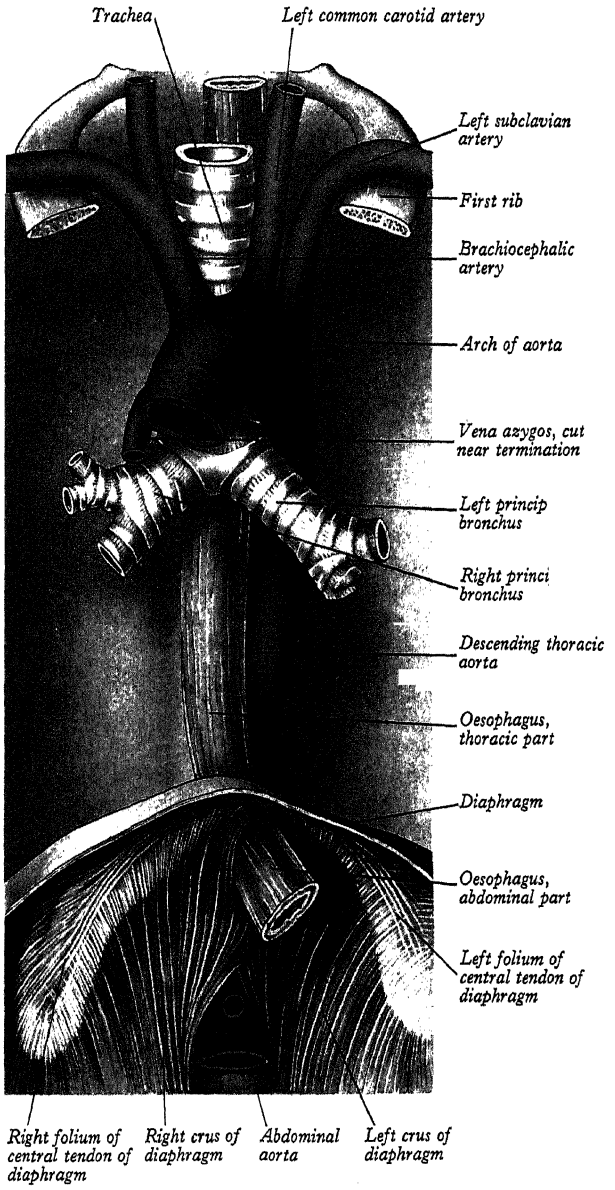
This is posterior to the trachea and attached to it by loose connective tissue; the recurrent laryngeal nerves ascend on each side in or near the groove between the trachea and the oesophagus; **posterior** are the vertebral column, longus colli and prevertebral layer of deep cervical fascia; **lateral** on each side are the common carotid artery and posterior part of the thyroid gland. In the lower neck, where the oesophagus deviates left, it is closer to the left carotid sheath and thyroid gland than it is on the right. The thoracic duct ascends for a short distance along its left side.

Thoracic part (12.83, 11.59, 60, 46)

At first situated a little to the left in the *superior mediastinum* between the trachea and the vertebral column, this passes behind and to the right of the aortic arch to descend in the posterior mediastinum along the right side of the descending thoracic aorta. Below, as it inclines left, it crosses anterior to the aorta to enter the abdomen through the diaphragm at the level of the tenth thoracic vertebra.

Anterior (from above downwards) are: the trachea, right pulmonary artery, left principal bronchus, pericardium (separating it from the left atrium) and the diaphragm; **posterior** are the vertebral column, longus colli muscles, right posterior (aortic) intercostal arteries, thoracic duct, azygos vein and the terminal parts of the hemiazygos and accessory hemiazygos veins and, near the diaphragm, the aorta. In the posterior mediastinum there is a long recess of the right pleural sac between the oesophagus in front and the vena azygos and vertebral column behind.

Left lateral, in the superior mediastinum, are the terminal part of the aortic arch, the left subclavian artery, thoracic duct, the left pleura and the recurrent laryngeal nerve which ascends in or near



12.83 and

the groove between the oesophagus and trachea. In the *posterior mediastinum* the oesophagus is related to the descending thoracic aorta and left pleura. *Right lateral* it is related to the right pleura, with the azygos vein intervening as it arches forwards above the right principal bronchus to join the superior vena cava. Below the pulmonary roots the vagus nerves descend in contact with the oesophagus, the right chiefly behind and the left in front, uniting to form an oesophageal plexus around it (p. 1253). Low in the posterior mediastinum the thoracic duct is behind and to the right; higher, it is posterior, crossing to the left at about the level of the fifth thoracic vertebra and then ascending on the left. On the right of the oesophagus, just above the diaphragm, a small serous *infracardiac bursa* may occur, representing the detached apex of the right pneumato-enteric recess.

Abdominal part (12.87–89)

This emerges from the right diaphragmatic crus (p. 816), slightly left of the midline and level with the tenth thoracic vertebra, grooving the posterior surface of the left lobe of the liver. It forms a truncated cone, about 1 cm long, curving sharply left, its base continuous with the cardiac orifice of the stomach; its right side continues smoothly into the lesser curvature, while the left is separated from the gastric fundus by the cardiac notch. Covered by peritoneum on its front and left side, it is contained in the upper left part of the lesser

omentum; the peritoneum reflected from its posterior surface to the diaphragm is part of the gastrophrenic ligament (p. 1739), through which oesophageal branches of the left gastric vessels reach it. Posterior are the left crus and left inferior phrenic artery. The relations of the vagus nerves vary as the oesophagus traverses the diaphragm (Doubilet et al 1948). Usually the *left* vagus is composed of two or three trunks firmly applied to the anterior aspect of the oesophagus; the *right* vagus is usually single, a thick cord some distance from the posterior aspect of the oesophagus.

OESOPHAGEAL MICROSTRUCTURE (12.82, 84, 85)

The organization of tissues within the oesophageal wall follows the general pattern outlined above, namely (from lumen outwards), the mucosa consisting of epithelium, lamina propria, and muscularis mucosae; then the submucosa, muscularis externa, and adventitia, or, below the level of the diaphragm, serosa instead of adventitia.

Mucosa

The mucosa is thick and, in the living, pink above but pale below. At its lowermost end, at the gastro-oesophageal junction, there is an abrupt transition, the crenated boundary line separating the greyish-pink, smooth, oesophageal mucosa from the red, mamillated, gastric mucosa. Throughout its length, the oesophageal lumen is marked by deep longitudinal grooves and ridges which disappear when the lumen is distended but obliterate the lumen at all other times.

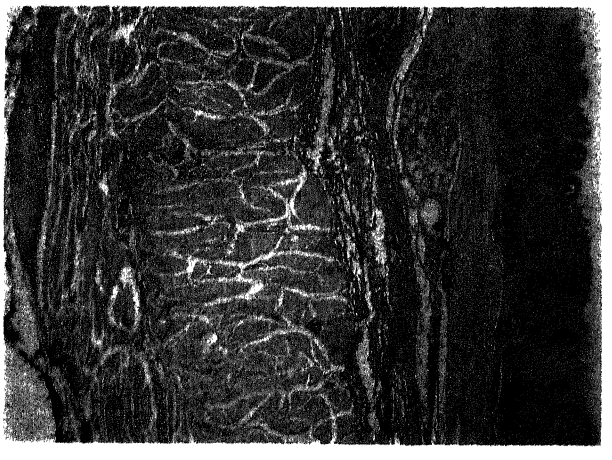
Epithelium. Non-keratinized stratified squamous in type, it is continuous with that of the pharynx. In humans this protective layer is quite thick (300–500 μm: see **12.84**, a property not affected by oesophageal distension. At the gastro-oesophageal junction the stratified squamous epithelium is abruptly succeeded by simple columnar epithelium with gastric pits and glands (p. 1758). The boundary between the general oesophageal epithelium and the lamina propria undulates and tall connective tissue papillae invaginate the epithelial base (**12.85, 86**) assisting in the anchorage of the epithelium to the underlying tissues. These papillae are permanent structures, unaffected by oesophageal distension; they are rich in blood vessels and nerve fibres. At the base of the epithelium is a basal lamina, to which epithelial cells are attached by hemidesomes, as in the oral mucosa. Similar to other stratified replacing epithelial, the oesophageal epithelium can be divided into:

- a basal, proliferative layer
- a parabasal layer of cells undergoing terminal differentiation
- a flattened layer of superficial cells or squames (sometimes termed the stratum corneum although its cells are nucleated).

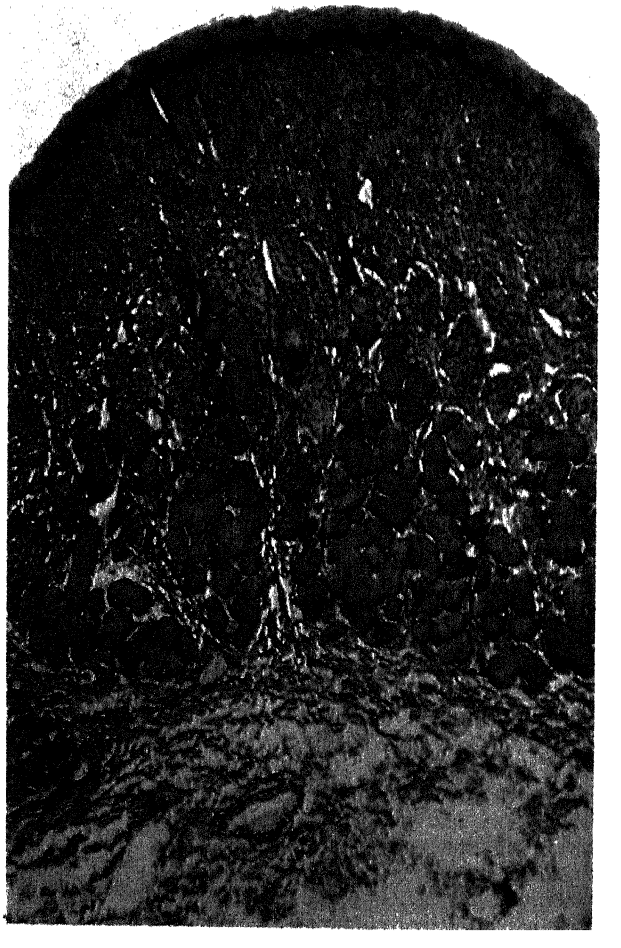
The deepest cells are attached basally to the underlying basal lamina, and the parabasal cells to each other by numerous desmosomes. Between these cells the narrow spaces are filled with proteoglycans which are stainable with alcian blue or demonstrable by electron microscopy after tannic acid fixation (Hopwood et al 1994). Cytokeratins similar to those of the oral mucosa are present in the epithelium, their precise immunochemical identity changing as the cells migrate apically. The most superficial strata of cells also contain a few keratohyalin granules in addition to cytokeratin filaments and nuclei. For further ultrastructural details see Hopwood et al 1978.

The epithelial cell population is constantly renewed by mitosis of the cuboidal basal cells and the deepest of the parabasal cells. As they migrate towards the lumen they become progressively polygonal then more flattened, eventually being desquamated at the epithelial surface. This sequence of events normally takes 2–3 weeks, and is markedly slower than in the stomach and intestine (MacDonald et al 1964); however, it is greatly affected by the mechanical conditions at the luminal surface. In rodents, where the oesophageal epithelium is keratinized, the renewal rate of these epithelial cells is faster than in man, and the cells migrate through the thickness of the epithelium in about 1 week.

Barrier functions. Although it appears to lack tight junctions between its cells, the oesophageal epithelium is a considerable permeability barrier. Tracers such as horseradish peroxidase (HRP) placed in the lumen fail to penetrate its surface, while if introduced into the lamina propria, the tracer diffuses superficially to about two-thirds the thickness of the epithelium but is then stopped



12.84 A low-power micrograph of a vertical section through the wall of a human oesophagus taken in the upper thorax. Visible in this section are: the epithelium (blue-grey on the right), the lamina propria, muscularis mucosae, submucosa with a group of mucous glands, the external muscle with the circular fibres more deeply placed and the longitudinal fibres placed externally. See text for further description. Mallory's triple stain. Magnification ×6. (Prepared by W Owen, Department of Anatomy, Guy's Hospital Medical School, London.)



12.85 Low magnification light micrograph of a section of the oesophagus showing the stratified squamous non-keratinized epithelium lining it and mucous glands (stained turquoise) of the submucosa. Weigert and Van Gieson, with alcian blue. (Prepared by David Ristow; photographed by Marina Morris, Department of Anatomy, Guy's Hospital Medical School, London.)

(Orlando et al 1992). The nature of this barrier is not certain, but it is likely that the proteoglycans between the cells play an important part. Because of its thickness and the presence of mucus at its surface, the epithelium is also a good protection against mechanical injury. However, it is only a limited protection if exposed repeatedly to the very acid, protease-rich secretions of the stomach, as occurs abnormally during reflux. Normally the lower oesophageal sphincter prevents such an occurrence (see below), but if it does occur, ulceration and fibrosis of the oesophageal wall accompanied by considerable pain and difficulties in swallowing may ensue. Exposure to acid may also cause an epithelial redifferentiation to a gastric-like mucosa (Barrett's mucosa), or to more overt neoplastic changes (Hamilton 1990).

Langerhans cells. Besides replacing epithelial cells, *Langerhans cells* also occur in the oesophageal epithelium (Al-Yassin & Toner 1976; Geboes et al 1983). These dendritic cells resemble those of the epidermis, and are thought to carry out similar antigen-presenting activities which are important in the immune defence of the mucosa and surrounding tissues (see p. 1415).

Lamina propria. This has already been referred to. In addition to its supportive functions, it contains scattered groups of lymphoid follicles which are especially prominent near the gastro-oesophageal junction. Small tubular mucous glands also occur in this region and in the upper part of the oesophagus close to the pharynx.

Muscularis mucosae. Composed of bundles of mainly longitudinal smooth muscle, this forms a sheet near the epithelium whose undulations it closely follows. At the pharyngeal end of the oesophagus it may be absent or represented merely by sparse, scattered bundles; below this it becomes progressively thicker. The longitudinal orientation of its cells changes to a more plexiform arrangement near the gastro-oesophageal junction.

Submucosa

The submucosa loosely connects the mucosa and the muscularis externa, and invades the longitudinal ridges of the oesophageal mucosa. It contains larger blood vessels, nerves and mucous glands. Its elastic fibres are also important in the reclosure of the oesophageal lumen after peristaltic dilatation.

Oesophageal glands. These are small compound tubulo-acinar glands lying in the submucosa, each group sending a single long duct through the intervening layers of the gut wall to the surface. They contain mainly mucous cells, although serous cells have also been described (Hopwood et al 1986). In the region close to the pharynx and at the lower end close to the stomach, the glands are simpler in form and restricted to the lamina propria: those of the abdominal oesophagus closely resemble the gastric cardiac glands (Johns 1952) and are termed *oesophageal cardiac glands*.

Muscularis externa

The muscularis externa is up to 300 μm thick; it has the usual outer longitudinal and inner circular layers. The longitudinal fibres form a continuous coat around almost the whole length of the oesophagus; but posterosuperiorly, 3–4 cm below the cricoid cartilage, they diverge as two fascicles ascending obliquely to the front of the tube. Here they pass deep to the lower border of the inferior constrictor, and finally they end in a tendon attached to the upper part of the ridge on the back of the cricoid lamina (**12.3**). The V-shaped interval between these fascicles is filled by circular fibres of the oesophagus, thinly covered below by some decussating longitudinal fibres and above by the overlapping inferior constrictor. The longitudinal layer is generally thicker than the circular. Accessory slips of smooth muscle sometimes pass between the oesophagus and left pleura or the root of the left principal bronchus, trachea, pericardium or aorta. These are sometimes considered to fix the oesophagus to these structures.

Superiorly the circular fibres are continuous behind with the inferior pharyngeal constrictor; in front, the uppermost are attached to the lateral margins of the tendon of the two longitudinal fasciculi of the oesophagus. Inferiorly, the circular muscle is continuous in the stomach wall with the oblique layer of its muscle fibres. As an approximation, skeletal muscle is limited to the upper two-thirds of the muscularis externa in the human oesophagus; the lower third contains only smooth muscle. In the upper quarter both layers are skeletal; in the second quarter smooth muscle appears, at first internally and below this it gradually replaces the skeletal muscle. Whitmore (1982), using primate (including human) material, has identified 'fast' and 'slow' twitch fibres in oesophageal skeletal muscle; he also observed that the striated musculature gave way to smooth muscle more gradually and proximally in primates than in rodents.

Lower oesophageal sphincter

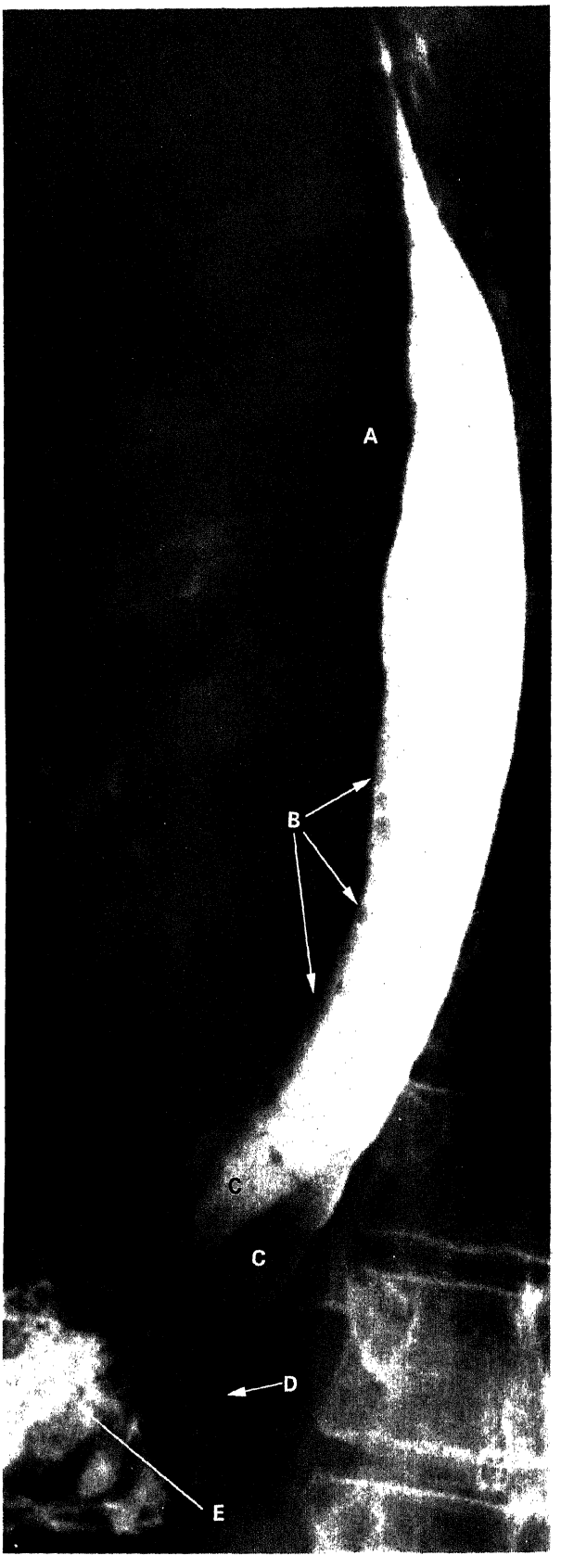
Radiological studies show that swallowed food stops momentarily in the gastric end of the oesophagus, before entering the stomach (**12.86**) suggesting the presence of a sphincter at this point. In the past there was much controversy about the reason for this behaviour (see e.g. DiDio & Anderson 1968; Code 1968), since only slight thickening of the muscle coat has been found in humans (although sphincteric muscle with a rich innervation has been described in macaque monkeys: Vaithilingham et al 1984). There is now ample physiological and clinical evidence that closure depends on two major mechanisms operating at the lower end of the oesophagus. The most important of these is the *lower oesophageal sphincter*, a specialized zone of circular smooth muscle surrounding the oesophagus at its transit through the diaphragm and for much of its short abdominal course. This region of the oesophagus is maintained under tonic contraction, except during swallowing when it relaxes briefly to admit ingesta to the stomach (Fyke et al 1956; Zaninotto et al 1988), and during vomiting. It is controlled by the intramural plexuses of the enteric nervous system, the neural release of nitric oxide contributing to its relaxation. The second mechanism is a functional *external sphincter* provided by the crural diaphragm, usually the right crus (p. 816) which encircles the oesophagus as it passes into the abdomen and is attached to it by the phrenoesophageal ligament (Bombeck et al 1966). Radiological, electromyographic and manometric analyses have shown that its muscular fibres contract around the oesophagus during inspiration and when intra-abdominal pressure is raised, thus helping to prevent gastro-oesophageal reflux, even when the lower oesophageal sphincter is inhibited experimentally with atropine (see the review by Ferrarini et al 1993). The relative importance of these two agents in the prevention of oesophageal reflux is still being debated; clinically, there is a good correlation of this condition with lower oesophageal sphincter dysfunction in some cases, whilst in others failure of the diaphragmatic component, as seen in hiatus hernia, appears to be a major factor. The anatomical configuration of the gastro-oesophageal orifice may also play some part in these processes (see below). For recent reviews of this topic, see Ferrarini et al (1993) and Kahrilas (1993).

STOMACH (12.71, 88–95)

The stomach (ventriculus or preferably *gaster*) is the most dilated part of the alimentary canal and is situated between the oesophagus and the small intestine; it lies in the epigastric, umbilical and left hypochondriac areas of the abdomen, occupying a recess bounded by the upper abdominal viscera and completed above and anterolaterally by the anterior abdominal wall and diaphragm. Its shape and position are modified by changes within itself and by the surrounding viscera. Its mean capacity varies from about 30 ml at birth, increasing to 1000 ml at puberty and about 1500 ml in adults. It has two openings and is described as if it had two borders or curvatures and two surfaces. In reality its external surface is a continuum and not divided by perceptible 'borders'. However, since its peritoneal surface is interrupted by the attachments of the greater and lesser omenta along profiles which define the gastric radiographic shadow, these curvatures may be conveniently regarded as 'borders' separating the surfaces.

GASTRIC ORIFICES

The opening from the oesophagus into the stomach is the *cardiac orifice* situated to the left of the midline behind the seventh costal cartilage, 2.5 cm (1 in) from its sternal junction at the level of the eleventh thoracic vertebra. It is about 10 cm (4 in) from the anterior abdominal wall and 40 cm (16 in) from the incisor teeth. The short abdominal part of the oesophagus, shaped like a truncated cone, curves sharply left as it descends, the base of the cone being



12.86 An oblique radiograph of the thorax during the oesophageal transit of part of a 'meal' of barium sulphate paste. At [A] the translucency of the air-containing right principal bronchus is visible. The concave ventral aspect of the oesophagus [B] is topographically related to the pericardium covering the left atrium of the heart. Longitudinal mucosal folds are visible [C] immediately proximal to the soft tissue shadow of the diaphragm [D]. Some barium sulphate is already admixed with the gastric contents [E]. The oesophagus in the lower thorax curves ventrally away from the vertebral column to reach the oesophageal orifice in the diaphragm.

continuous with the cardiac orifice. The right side of the oesophagus is continued as the *lesser curvature*, while its left side joins the *greater curvature* at an acute angle, the *cardiac notch* or *incisure*. The *cardia* is the region immediately adjacent to the cardiac orifice. The part of the stomach above the level of the cardiac orifice is the *fundus*, an inappropriate term, but it is the **bottom** of the stomach, when entered surgically from below.

The *pyloric orifice*, the opening into the duodenum, is usually indicated (**12.87, 88, 90, 91**) by a circular *pyloric constriction* on the surface of the organ, indicating the pyloric sphincter; it can be identified by the prepyloric vein crossing its anterior surface vertically. The pyloric orifice is about 1.2 cm (0.5 in) to the right of the midline in the transpyloric plane (level of the lower border of the first lumbar vertebra), with the body supine and the stomach empty.

GASTRIC CURVATURES (12.87, 88)

Lesser curvature. Extending between the cardiac and pyloric orifices, this is the right (posterosuperior) border of the stomach. It descends from the right side of the oesophagus in front of the decussating fibres of the right crus, curving to the right below the omental tuberosity of the pancreas to end at the pylorus. In the most dependent part there is typically a notch, or *incisura angularis (angular incisure)*, its position varying with gastric distension; it is sometimes used to define the right and left parts of the stomach. The lesser omentum is attached to the lesser curvature and contains the right and left gastric vessels adjacent to the line of the curvature.

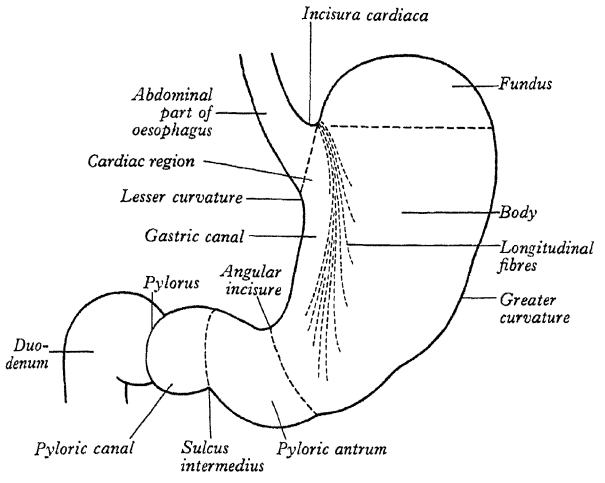
Greater curvature. This is directed antero-inferiorly and is four or five times as long as the lesser; it starts from the cardiac incisure and arches upwards posterolaterally and to the left; its highest convexity, the fundus, is level with the left fifth intercostal space just below the left nipple in males, though varying with respiration (pp. 818–819). From this level it sweeps down and forwards, slightly convex to the left, almost as far as the tenth costal cartilage in the supine body; it finally turns right to end at the pylorus. Opposite the angular incisure of the lesser curvature, the greater curvature presents a bulge, taken as the left limit of the *pyloric part* of the stomach, its right limit being a slight groove (*sulcus intermedius*) indicating subdivision into the *pyloric antrum* and *canal*, the latter only 2–3 cm in length and terminating at the pyloric constriction. The start of the greater curvature is covered by peritoneum continuous with that anterior to the stomach. Left of the fundus and the adjoining body of the stomach the greater curvature gives attachment to the gastrosplenic ligament and beyond this to the greater omentum, the two layers of which are separated by the gastro-epiploic vessels. The gastrosplenic ligament and the greater omentum (with the gastrophrenic and lienorenal ligaments, see p. 1738, **12.77A**) are continuous parts of the original dorsal mesogastrium (p. 183). The names merely indicate regions of the same fold.

GASTRIC SURFACES

When the stomach is empty and contracted, its surfaces are almost superior and inferior; but in distension they become anterior and posterior respectively, and are therefore described here as anterosuperior and postero-inferior surfaces.

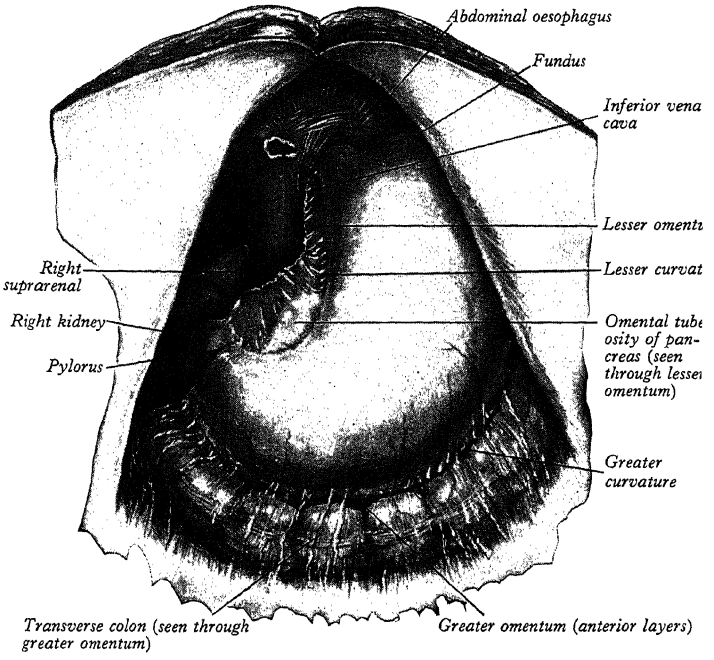
Anterosuperior surface. The left part of this surface is posterior to the left costal margin and in contact with the diaphragm which separates it from the left pleura, the base of the left lung, the pericardium and the left sixth to ninth ribs and intercostal spaces. It is related to the costal attachments of the upper fibres of the transversus abdominis, which separate it from the seventh to ninth costal cartilages. The upper and left part of this surface becomes posterolateral and is in contact with the spleen's gastric surface. The right half of the anterosuperior surface is related to the left and quadrate lobes of the liver and the anterior abdominal wall. When the stomach is empty, the transverse colon may lie on its anterior surface. The whole surface is covered by peritoneum and part of the greater sac separates it from the above structures.

Postero-inferior surface. This is related to the diaphragm, the left suprarenal gland, upper part of the front of the left kidney, the splenic artery, anterior pancreatic surface, left colic flexure and the transverse mesocolon (upper layer), which together form the shallow



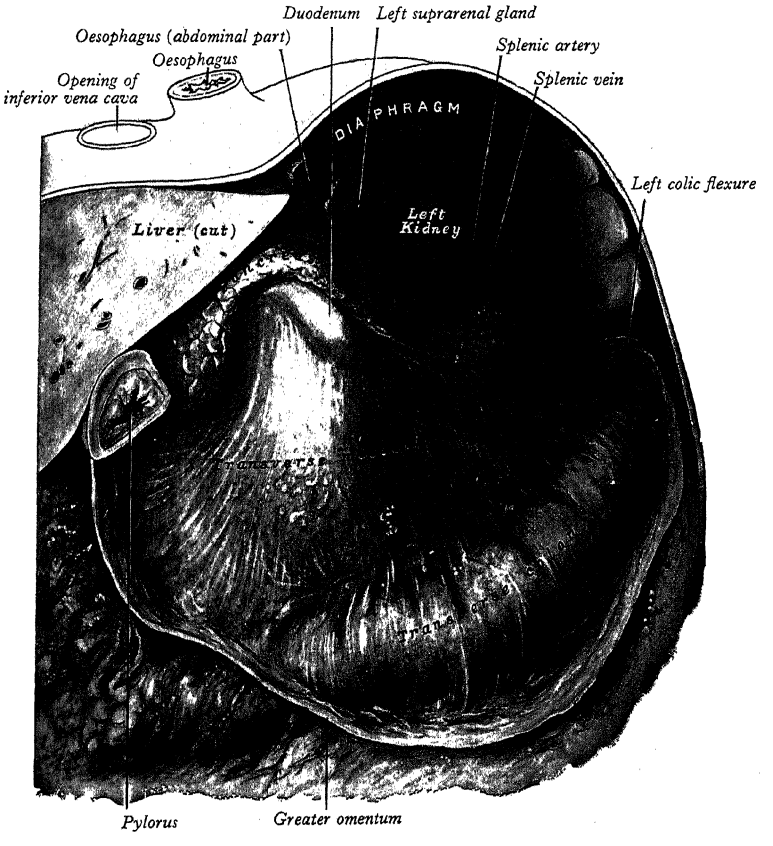
12.87 The parts of the stomach.

stomach bed (12.89), over which the stomach slides, due to the intervening lesser sac. The spleen's gastric surface is usually included in the stomach bed, though separated from the stomach by part of the greater sac. The greater omentum and the transverse mesocolon separate the stomach from the duodenojejunal flexure and small intestine. The postero-inferior surface is covered by peritoneum, except near the cardiac orifice, where a small, triangular area contacts the left diaphragmatic crus and sometimes the left suprarenal gland. The left gastric vessels reach the lesser curvature at the right extremity of this area in the left gastropancreatic fold (p. 1740); from its left side the *gastrophrenic ligament*, continuous below with the splenicorenal and gastrosplenic ligaments, passes to the diaphragm's inferior surface.

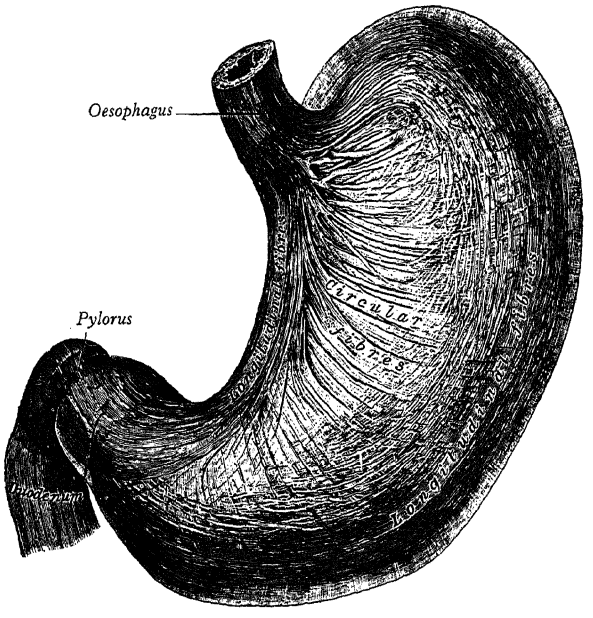


12.88 The stomach in situ, after removal of the liver.

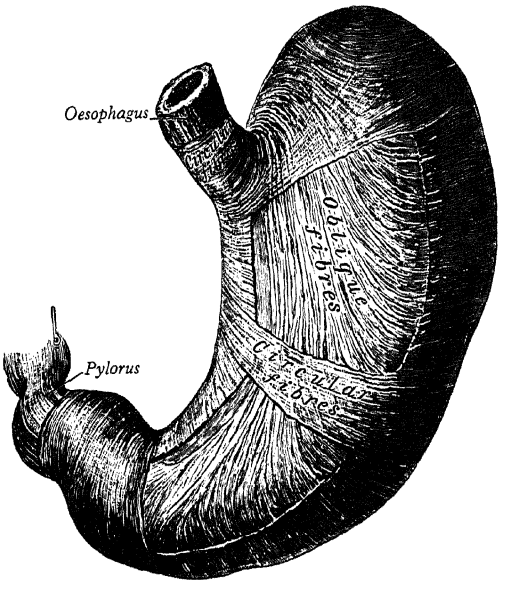
A plane passing through the angular incisure of the lesser curvature and the left limit of the opposed bulge on the greater curvature arbitrarily divides the stomach into a large *body* (left) and a smaller *pyloric part* (right).



12.89 The stomach bed: a dissection in which the stomach has been removed to show its posterior relations.



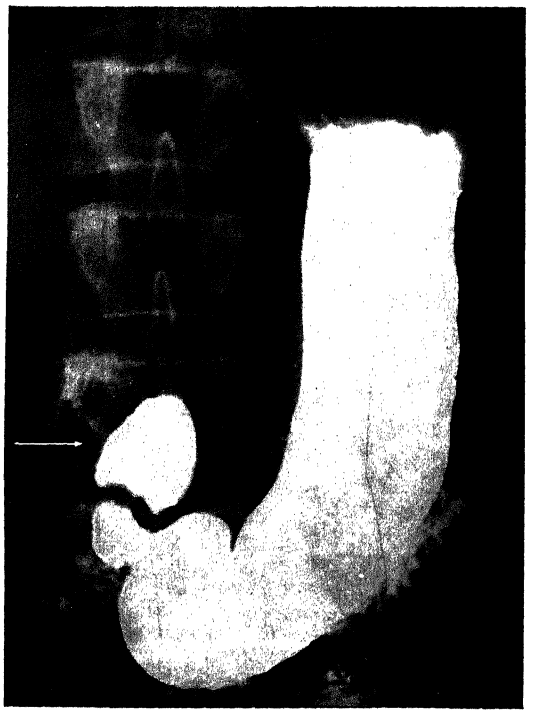
12.90A The longitudinal and circular gastric muscular fibres: anterosuperior aspect (Spalteholz).



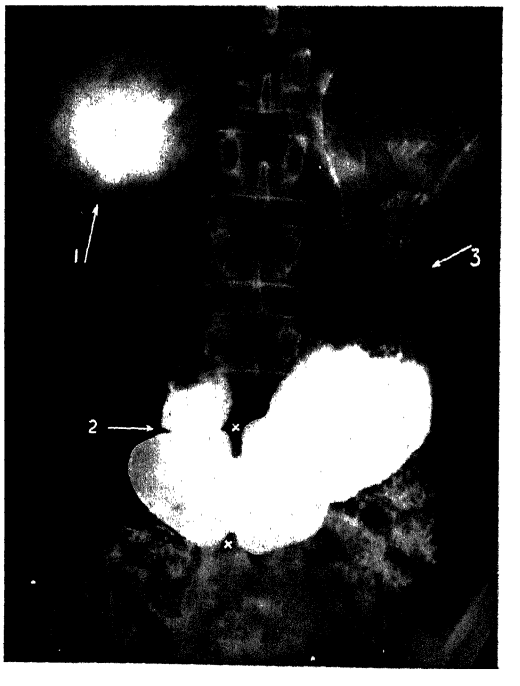
12.90B The oblique muscular fibres of the stomach, shown by partial dissection of its wall: anterosuperior aspect (Spalteholz).

RADIOLOGY

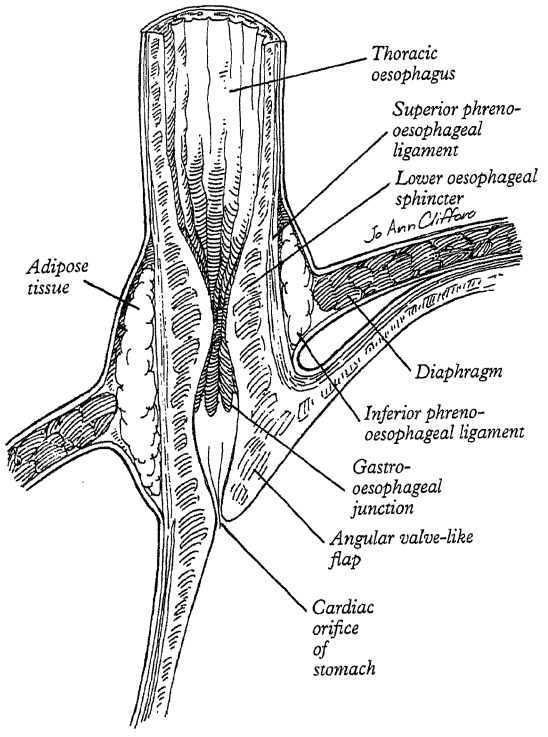
The form and position of the stomach can be studied after swallowing a suitable 'meal' containing barium sulphate (12.91, 92). During digestion it is divided by a muscular constriction in its body into a large, dilated, left region and a narrow, contracted, tubular right one. The constriction in the body follows no anatomical landmarks but moves gradually left as digestion progresses. The position of the stomach varies with posture, contents and the state of the intestines, on which it rests; it is also influenced by the tone of the abdominal wall and gastric musculature and by the individual's build. Most commonly the empty organ is J-shaped and, in the erect posture, the pylorus descends to the level of the second or the third lumbar vertebra, its most dependent part being subumbilical. The fundus usually contains gas. Variation in content mainly affects the body, the pyloric part remaining contracted during digestion. As the stomach fills it expands forwards and downwards but, when the colon or intestines are distended, the fundus presses on the liver and diaphragm and may evoke discomfort. When hardened in situ the contracted stomach is crescentic, the fundus directed backwards.



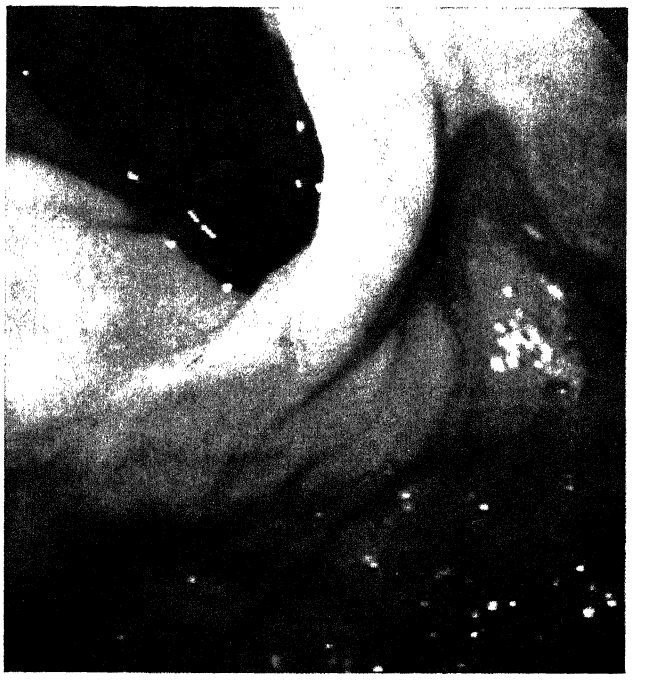
12.91 Radiograph of a normal stomach after a barium meal. The tone of the muscular wall is good and supports the weight of the column in the body of the organ. The arrow points to the duodenal cap, below which a gap in the barium indicates the position of the pylorus.



12.92 Radiograph of an atonic stomach after a barium meal. Note that this stomach contains the same amount of barium suspension as the stomach in 12.91. Arrow 1 points to the shadow of the right breast, arrow 2 to the pylorus, arrow 3 to the upper part of the body of the stomach, where longitudinal folds can be seen in the mucous membrane. XX marks a wave of peristalsis.



12.93A Diagram showing the valve-like structure formed by the cardiac angle wall at the cardiac orifice. (Provided by Donald E Low, Department of Surgery, Virginia Mason, Seattle, USA.)



12.93B Endoscopic view of the cardiac orifice from below, showing the valve-like fold illustrated in 12.93A. The black rod inserted in the orifice is the stem of the endoscope. (Provided by Donald E Low, Department of Surgery, Virginia Mason, Seattle, USA.)

Surfaces are superior and inferior, the former sloping gradually to the right, the greater curvature being anterior to and at a slightly higher level than the lesser.

The position of the full stomach varies. When the intestines are empty the fundus expands vertically and forwards, the pylorus is displaced right and the whole organ becomes oblique. Its surfaces are then directed more forwards and backwards, the lowest part being the pyloric antrum which extends below the umbilicus. When intestinal distention interferes with downward expansion of the fundus, the stomach retains the horizontal position characteristic of the contracted viscus. Less commonly it may lie almost transversely, even in the erect posture, as the '*steer-horn*' type. Intermediate types of stomach, between J-shaped and 'steer-horn', also occur (Barclay 1936).

INTERIOR OF THE STOMACH

After death the stomach is usually fixed at some stage of the digestive process, commonly as shown in 12.94). When it is laid open after section along the plane of its curvatures, it shows two segments:

- a large globular left part
- a narrow tubular right part

The transition is gradual, so their division is arbitrary. The cardiac incisure lies to the left of the abdominal part of the oesophagus and its projection into the cavity increases as the organ distends, supposedly acting as a valve preventing oesophageal regurgitation. The elevation opposite the angular incisure is at the beginning, and the circular thickening of the pyloric sphincter at the end, of the pyloric region.

Modelling of human fetal gastric epithelium (Lewis 1912) has shown that a *gastric canal* extends along the lesser curvature from the cardiac orifice to the angular incisure (12.87). Jefferson (1915) demonstrated such a canal radiologically in adults, and examination during the act of swallowing radio-opaque fluid showed that it was first confined to the region adjacent to the lesser curvature, suggesting that contraction of oblique muscle fibres causes temporary separation of a canal along the lesser curvature.

Pyloric sphincter. This is a muscular ring formed by a marked thickening of the circular gastric muscle, some longitudinal fibres also interlacing with it (DiDio & Anderson 1968.)

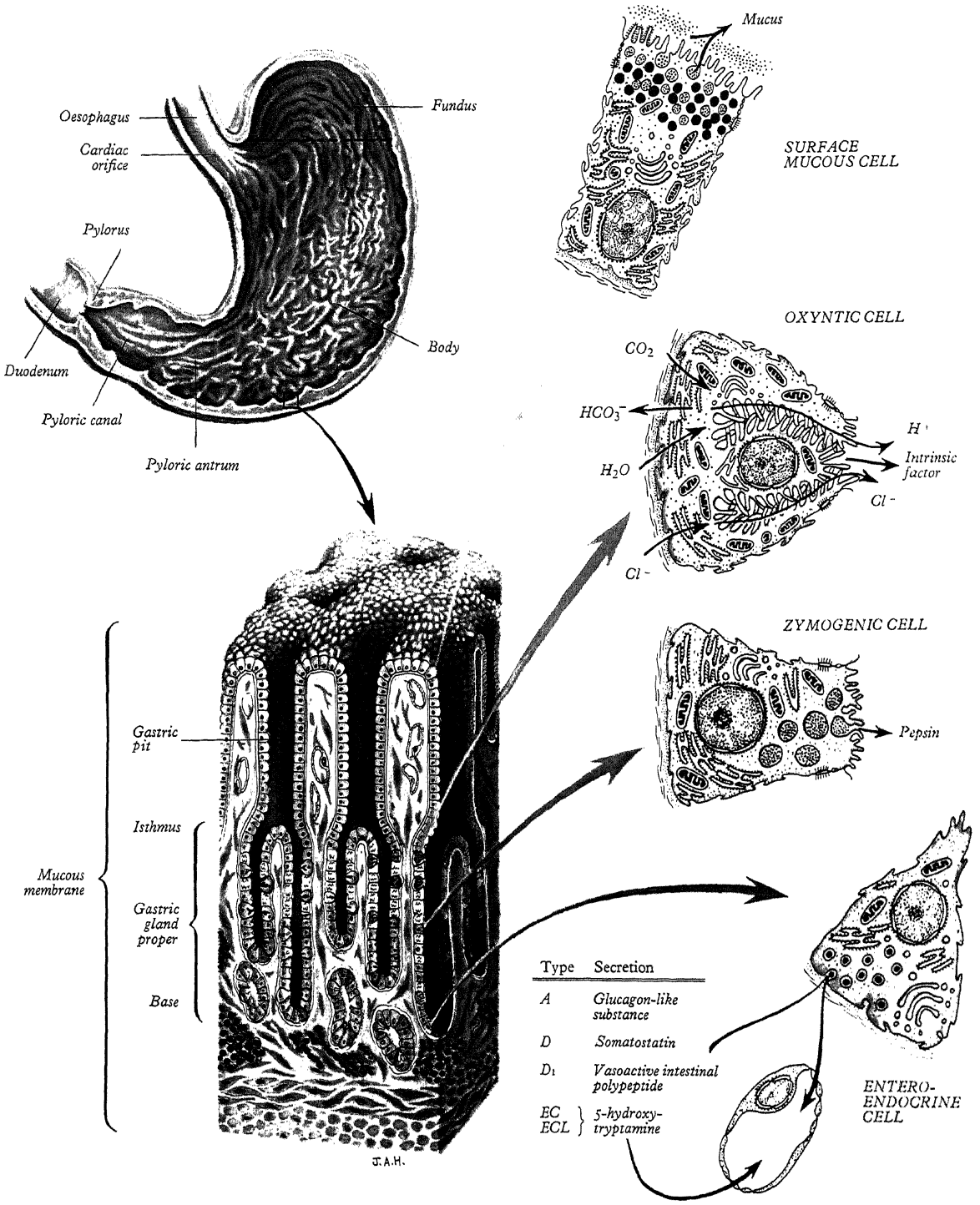
Cardiac sphincter. This sphincter is sometimes described as being formed from the circular fibres of the gastric wall. However, closure of the gastro-oesophageal junction appears to be performed by the tonic contraction of the lower oesophagus (see p. 1753).

Gastro-oesophageal junction. The transition between the oesophagus and stomach is difficult to define, as the gastric mucosa extends some distance up the tube of the abdominal oesophagus, forming a zig-zag squamo-columnar epithelial junction. The external muscle layers of the two organs also blend, except that a sling of longitudinal gastric muscle forms a loop on the superior, left side of the junction between the oesophagus and the lesser curvature, and this is often taken as the boundary for practical purposes.

The acute angle between the oesophagus and the upper part of the cardia (the angle of His or cardiac incisure) is extended within the lumen as a large fold. Because it is suitably positioned to act as a valvular flap (12.93A, B) which with raised intragastric pressure is likely to close the oesophageal entrance, it has been proposed as a mechanism additional to the lower oesophageal sphincter (p. 1753), limiting oesophageal reflux of gastric fluids by occluding the entrance to the oesophagus when intragastric pressure is raised. The acute oesophagogastric angle and thus the valve disappear in hiatus hernia and, when patients have symptoms and complications of gastro-oesophageal reflux which cannot be controlled with medicines, they will often undergo surgery to re-establish an antireflux barrier. The various operations which are currently utilized in these patients accomplish this goal by reducing any hiatal hernia which is present back into the abdominal cavity and rebuilding a functional flap valve mechanism.

GASTRIC MICROSTRUCTURE (12.94, 95)

The gastric wall consists of the major layers found elsewhere in the gut, i.e. mucosa, submucosa, muscularis externa and serosa, together



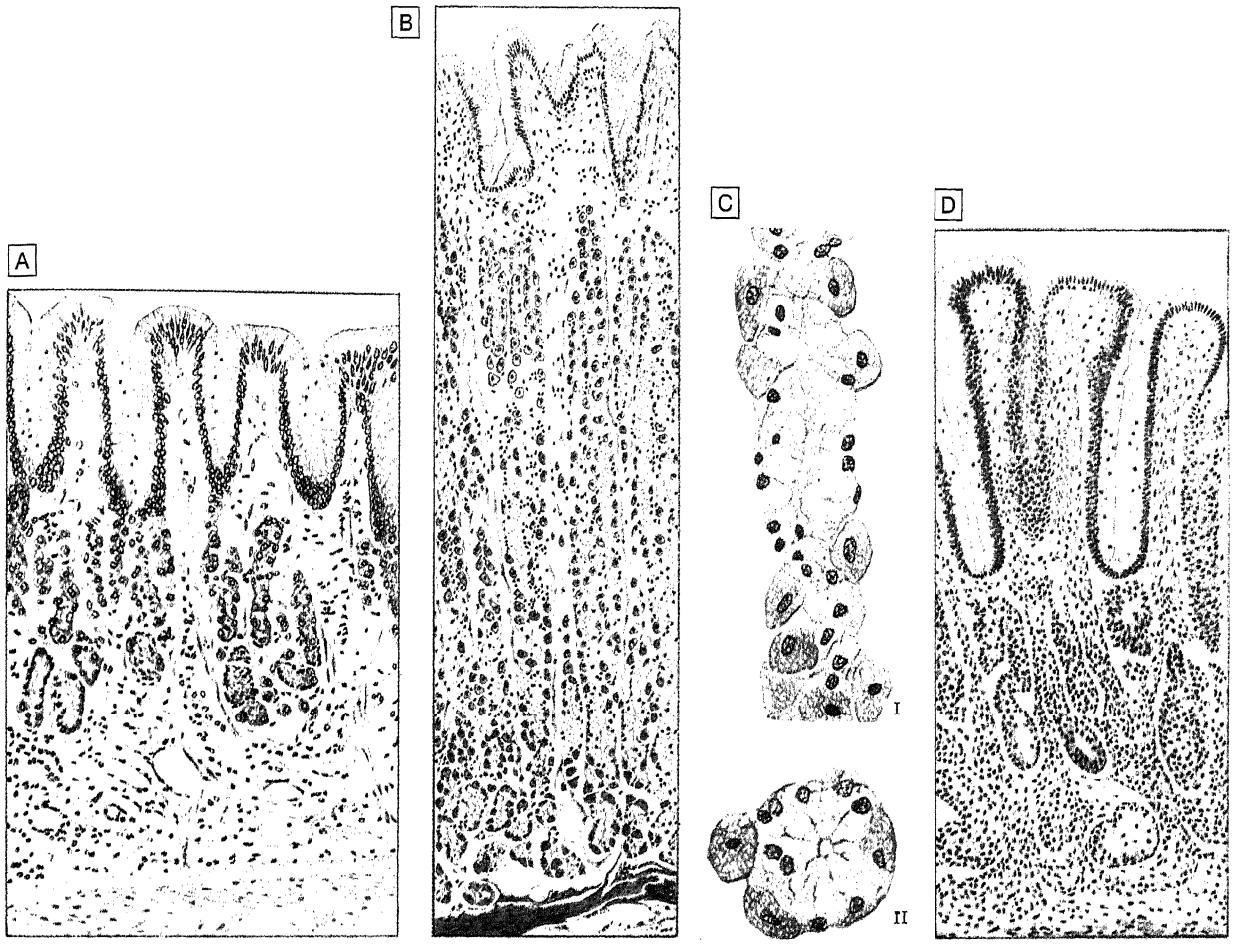
12.94 Diagram showing the principal regions of the interior of the stomach and the histology and ultrastructure of its mucous membrane. Undifferentiated, dividing cells are shown in white.

with gastric vessels and nerves. The microstructure of these reflects the functions of the stomach as an expandable, muscular sac lined by secretory epithelium, although there are local structural and functional variations in this pattern.

Mucosa

The mucosa is a thick layer, its surface smooth, soft, velvety and, over most of its surface, reddish brown in life; it is pink in the pyloric region. In the contracted stomach the mucosa is folded into numerous folds or *rugae*, most of which are longitudinal; they are most marked towards the pyloric end and along the greater curvature (**12.93**). The rugae represent large folds in the submucosal connective tissue (see below) rather than variations in the thickness of the mucosa covering them, and they are obliterated when the wall is stretched in gastric distension. As elsewhere in the gut, the mucosa is composed of a surface epithelium, lamina propria and muscularis mucosae.

Epithelium. When viewed microscopically at low magnification, the internal surface of the stomach wall (**12.95A, B, D**) appears honeycombed by small somewhat irregular *gastric pits* (foveolae), polygonal or slit-like funnel-shaped depressions about 0.2 mm in diameter. The base of each gastric pit receives several long tubular



12.95[A] Vertical section through the mucous membrane of the cardiac part of the stomach (human). Stained with haematoxylin and eosin. Magnification c. x 150.
12.95[B] Vertical section through the mucous membrane of the fundus of the stomach (cat). Note the beaded appearance given by the oxyntic cells. Stained with haematoxylin and eosin. Magnification c. x 100.
12.95[C] (I) Gland from the fundus of the stomach (cat). (II) Lower part of the gland cut transversely. Stained with haematoxylin and eosin. The peripherally placed cells staining deeply with eosin are the oxyntic cells. Magnification c. x 530.
12.95[D] Vertical section through the mucous membrane of the pyloric part of the stomach (cat). Stained with haematoxylin and eosin. Magnification c. x 75.

gastric glands which extend deep into the lamina propria as far as the muscularis mucosae. Simple columnar mucus-secreting epithelium covers the entire luminal surface including the gastric pits, composed of a continuous layer of *surface mucous cells* which liberate gastric mucus from their apices to form a thick protective, lubricant layer over the gastric wall (see below). This epithelium commences abruptly at the cardiac orifice, where there is a sudden transition from the oesophageal stratified epithelium.

Gastric glands. Although all are tubular, they vary in form and cellular composition in different parts of the stomach. They can be divided into the following categories (see Ito & Winchester 1963):

- cardiac
- principal (in the body and fundus)
- pyloric glands.

All are tubular, sometimes branched structures. The most highly differentiated are the principal glands, and these will be described first.

Principal gastric glands. These are found in the body and fundus, three to seven opening into each gastric pit; (**12.94**, **95**A, B). Their confluence with the base of the pit is termed the *isthmus* of the gland and immediately basal to this is the *neck*, the remainder being the *base*. In the walls of the gland are at least five distinct cell types: chief, parietal, mucous neck, stem and enteroendocrine, as follows:

- The *chief (peptic or zymogenic) cells* (**12.94**, **95**) are the source of the digestive enzymes pepsin and renin. They are usually basal in position, their shape being cuboidal and their nuclei rounded and open-faced. They contain secretory granules and because of the abundant cytoplasmic RNA they are strongly basophilic. Ultrastructurally they show typical features of active protein secretors, namely a copious granular endoplasmic reticulum, well-developed Golgi apparatus, large dense rounded secretory vesicles (containing pepsinogen), and interspersed lysosomes. At their lumen they bear short microvilli.

The *parietal (oxyntic) cells* are the source of gastric acid and of intrinsic factor. They are large, oval and strongly eosinophilic, with centrally placed nuclei; they are mainly sited in the more apical half of the gland, reaching as far as the isthmus. They occur only at intervals along the walls, and bulge laterally into the encircling connective tissue, giving the glands a beaded appearance (**12.95**B, C). At the luminal surface of the gland they appear recessed between neighbouring cells. Parietal cells have a unique ultrastructure clearly related to their remarkable ability to secrete hydrochloric acid. The luminal side of the cell is deeply and tortuously invaginated to form a series of deep blind-ending channels (*canaliculi*) furnished with numerous irregular

Within the cytoplasm facing these channels are myriads of fine membranous tubules (the *tubulo-vesicular system*) directed towards the canalicular surface. Abundant mitochondria are interspersed among these organelles. The membranes lining the microvilli have a high concentration of H^+/K^+ATPase antiporter channels which actively secrete hydrogen ions into the lumen, chloride ions following along the electrogenic gradient. The precise structure of

the cell varies with its secretory phase: when stimulated to secrete the numbers and surface areas of the microvilli increase up to five-fold, an event thought to be caused by the addition of membrane by rapid fusion of the tubulo-vesicular system with the plasma membrane, accompanied by polymerization of g-actin into actin filaments supporting the microvilli. At the end of stimulated secretion, this process is reversed, the excess membrane retreating back into the tubulo-alveolar system and the microvilli being erased. Parietal cells also contain a prominent Golgi body and a modicum of granular endoplasmic reticulum, which amongst other functions, must be responsible for the synthesis and secretion of *intrinsic factor*, a glycoprotein necessary for the absorption of vitamin B_{12}.

- *Mucous ('neck') cells* are numerous at the necks of the glands, and also scattered along the walls of the more basal regions. They are typical mucus-secreting cells, with numerous apical secretory vesicles containing mucins, and basally displaced nuclei. However, their products are distinct histochemically from those of the superficial mucous cells.
- *Stem cells* are relatively undifferentiated mitotic cells from which the other types of gland cell already mentioned are derived. They are relatively few in number, and are situated in the isthmus region of the gland and bases of the gastric pits. These calls are columnar in form, with a few short apical microvilli; internally their organelles are typical of stem cells in general, with a central open-face nucleus, large nucleolus and scattered polyribosomes with sparse granular endoplasmic reticulum. They periodically undergo mitosis, the cells they produce migrating apically to differentiate into new surface mucous cells, or basally to form mucous neck, parietal and chief cells, and also possibly the enteroendocrine cells (see p. 1787). All of these cells have limited lifespans, especially the mucus-secreting types, and need constant replacing. The replacement period for surface mucous cells is about 3 days; mucous neck cells are replaced after about 1 week. Other cell types appear to live much longer.
- *Enteroendocrine cells* occur in all types of gastric gland but more frequently in the body and fundus. They are situated mainly in the deeper parts of the glands, among the zymogenic cells. They are columnar cells with irregular nuclei surrounded by granular cytoplasm which can be stained strongly with silver salts (hence the older term, *argentaffin cells*). Ultrastructurally their luminal surface bears short microvilli, whilst at their base, facing the lamina propria and intervening basal lamina, they have clusters of large (0.3 μm) secretory granules synthesized in the granular endoplasmic reticulum and infranuclear Golgi apparatus for release into the surrounding tissues. These cells secrete a number of biogenic amines and polypeptides important in the control of motility and glandular secretion. In the stomach they include cells designated as G-cells secreting gastrin, D cells (somatostatin), and EC cells (see p. 1787). They form part of the enteroendocrine system of the alimentary tract and related organs, described further on p. 1787.

Cardiac glands. These are confined to a small area near the cardiac orifice (**12.95A**); some are simple tubular glands, others are compound branched tubular. Mucus-secreting cells predominate and parietal and zymogenic cells are few, although present.

Pyloric glands. Pyloric glands enter as groups of two or three short convoluted tubes into the bases of the deep gastric pits of the pyloric antrum which occupy about two-thirds of the mucosal depth (**12.94**). Pyloric glands are mostly furnished with mucus-secreting cells, parietal cells being few and chief cells mainly absent. Enteroendocrine cells are numerous however, especially G-cells secreting gastrin when activated by appropriate mechanical stimulation, causing increased gastric motility and secretion of gastric juices (see also p. 1787). Although parietal cells are few in pyloric glands, they are always present in fetal and postnatal material; in adults they may also appear in the duodenal mucosa but only proximally, near the pylorus (Leela & Kanagasuntheram 1968).

Lamina propria. Found between the glands, this forms a connective tissue framework and contains lymphoid tissue which, especially in early life, collects in small masses, termed gastric lymphatic follicles, resembling solitary intestinal follicles. A complex periglandular vascular plexus is also present and is thought to be important in the maintenance of the mucosal environment, including the removal of bicarbonate produced in the tissues as a counterpart to acid secretion. Neural plexuses are also present; these are both sensory and motor terminals (see p. 1307).

Muscularis mucosae. This is a thin stratum of smooth muscle fibres lying external to the layer of glands. Its fibres are arranged as inner circular and outer longitudinal layers, with a third external, circular layer in places. The inner layer sends strands of smooth muscle cells between the glands, contraction probably aiding their emptying.

Submucosae

The submucosa is a variable layer of loose connective tissue containing thick collagen bundles and numerous elastin fibres; blood vessels and nervous plexuses are also present including the ganglionated submucosal plexus of the stomach.

Muscularis externa

The muscularis externa is a coat immediately under the serosa, with which it is closely connected by subserous loose connective tissue. From within outwards it has *oblique, circular* and *longitudinal* layers of smooth muscle fibres. Further details of the macroscopic organization of the gastric muscle are given below.

Serosa or visceral peritoneum

The serosa covers the entire surface except:

- along the greater and lesser curvatures at the attachment of the greater and lesser omenta, where the peritoneal layers leave space for vessels and nerves
- a small postero-inferior area, near the cardiac orifice, where the stomach contacts the diaphragm at the reflexions of the gastrophrenic and left gastropancreatic folds.

GASTRIC MUSCLE

Topographic organization of layers

The three layers of the muscularis externa form distinct tracts which can be demonstrated by dissection (**12.90, 91**). Viewed from outside, the *oblique fibres* are deepest; they are limited in distribution to the gastric body and are most developed near the cardiac orifice. They sweep down from the cardiac incisure more or less parallel with the lesser curvature, near which they present a free and well-defined margin; on the left they blend with the circular fibres nearer the greater curvature. *Circular fibres* form a uniform layer over the whole stomach external to the oblique fibres. At the pylorus they are most abundant, aggregated into the annular pyloric sphincter; they are also continuous above with the circular fibres of the oesophagus but sharply separated from those of the duodenum by a septum of connective tissue. *Longitudinal fibres* are the most external; they are arranged in two groups. The first set is continuous with the longitudinal oesophageal fibres; radiating from the cardiac orifice, they are best developed near the curvatures and end proximal to the pyloric region. The fibres of the second group commence in the body and pass to the right, becoming thicker as they approach the pylorus; some superficial fibres pass to the duodenum, deeper ones turning inwards to interlace with the fibres of the pyloric sphincter.

Gastric muscle action

The gastric musculature can be divided functionally into:

- an upper region comprising the fundus, cardia and the superior part of the body of the stomach which form an area of storage;
- a lower region made up of the lower part of the gastric body and the pyloric antrum, which has a pump-like action mixing the stomach contents and delivering the semi-fluid chyme to the duodenum through the pyloric canal.

The muscle of the upper region exerts a maintained moderate tonic contraction on the stomach contents, whereas the lower muscle is much more motile, repeated peristaltic waves passing along this part of the stomach towards the pylorus when stimulated by the presence of food. The pyloric sphincter, which is open in the resting state, contracts as each peristaltic wave advances, narrowing it so that

only finely divided material and fluids can pass through its aperture, larger material being forced back into the pyloric antrum for further digestion and diminution.

GASTRIC VESSELS

Arteries

The arterial supply comes from the left gastric artery (directly from the coeliac artery), right gastric and right gastro-epiploic (from the common hepatic) and the left gastro-epiploic and short gastric (from the splenic) artery. These vessels not only anastomose extensively on the serosal aspect of the stomach (p. 1548) but also form anastomotic networks within its walls at intramuscular, submucosal and mucosal levels; a true plexus of small arteries and arterioles is present in the submucosa. This *submucosal plexus*, from which the mucosa is supplied, shows considerable regional variation both in the gastric wall and also in the proximal duodenum.

In view of a possible vascular factor in the genesis of peptic ulcers, the local details of angioarchitecture are of interest. For a review of the older literature see the study by Piasecki (1974, 1977), who studied the arterial supply in fetal, neonatal and adult human stomachs, using India ink injections of fresh post mortem specimens (**12.96**A). From anastomotic arcades along the greater and lesser curvatures, formed by the main arteries of supply described above, many *anterior* and *posterior gastric arteries* pass to the anterior and posterior aspects of the stomach, approximately transverse to the organ's long axis. Smaller rami, often paired, also pass directly to parts of the gastric wall subjacent to the omental attachments.

All these vessels ramify on the external surface and penetrate the muscular layers to reach the submucosa and mucosa, forming subserosal, intramuscular and submucosal plexuses, the second of these being the best developed (**12.96**A, B). This muscular plexus is supplied by branches from the subserous and submucosal plexuses; the muscular vessels vary in their direction in different muscular laminae, perhaps adapting to directions of contraction. Submucosal arteries anastomose freely, but the incidence of anastomoses varies. Counts by Piasecki (1974) showed that while anastomoses along, e.g. the lesser curvature, increased in **number** from cardia to pylorus; the mean **calibre** of anastomosing arteries showed a reverse tendency. Mucosal arteries, which fill the capillary networks supplying the epithelium and its glands, are mainly from the submucosal plexus; but along both curvatures a few mucosal arteries come directly from subserosal sources, traversing the muscular layers and submucosa, often without lateral junctions with submucosal arteries; their frequency apparently increases from the cardiac to the pyloric regions; the capillary networks supplied by them are largely independent of those fed by adjacent submucosal arteries and the patch of mucosa supplied by such a vessel is perhaps more vulnerable to vascular obstruction.

Piasecki also showed a different pattern of supply in the pyloric canal and sphincter. 'Pyloric arteries', rami of the right gastric and gastro-epiploic arteries, pierce the duodenum distal to the sphincter around its entire circumference, passing through the muscular layer to the submucosa where each divides into two or three rami, which turn into the pyloric canal, internal to the sphincter; they traverse the submucosa to the end of the pyloric antrum (**12.96**B), supplying the whole mucosa of the pyloric canal. Branches of these pyloric submucosal arteries may anastomose at their commencement with the duodenal submucosal arteries and, by their terminal rami, with corresponding gastric arteries. The pyloric sphincter is supplied by the gastric and pyloric arteries, whose rami leave their parent vessels in the subserosal and submucosal levels to penetrate the sphincter. In a more recent study, Piasecki (1986) has described arrangements in a large number of animals, including rodents, swine, cats, dogs and monkeys, with little modification from the pattern he found earlier in primates.

Veins

These commence as straight vessels between the mucosal glands and drain into the submucosal veins. Their further arrangement has not received as much attention as that of the corresponding arteries; but the larger veins generally accompany main arteries to their ultimate drainage into the splenic and superior mesenteric veins, while some pass directly to the portal vein.

Lymphatic vessels

These smaller vessels are said to resemble the veins in distribution. Regional lymph nodes and their drainage are described on p. 1619.

Microvasculature of the gastric mucosa

Functionally the microvessels of the mucosa are thought to be important in protecting its cells against the extremely acid conditions of the gastric lumen (see Gannon et al 1984, Raschke et al 1987 for studies and reviews of this subject). The mucosa has a rich blood supply, its pattern varying in different regions of the stomach, although there is some difference of opinion as to its detailed organization. It is generally accepted that arterioles from the submucosal arterial plexus penetrate into the mucosa and branch to form rich capillary beds around the gastric glands, anastomizing laterally with each other, and conveying blood towards the mucosal surface where they drain into rather sparsely scattered venules leading back to the submucosal venous plexus. It has been proposed that the rich lumen-directed flow of blood enables bicarbonate generated basally by parietal cells as a counterpart of their secretion of acid, to be carried into the apical parts of the mucosa so as to protect its cells against acid damage. It is also interesting that the capillaries in this area are fenestrated, a feature likely to facilitate the delivery of bicarbonate to the surface regions of the mucosa. In the gastric antrum where there are few or no bicarbonate-secreting parietal cells, the capillary beds and their blood supply are even richer, and the apical and basal regions of the mucosa receive separate arteriolar supplies (Gannon et al 1984), perhaps to increase the perfusional removal of acid.

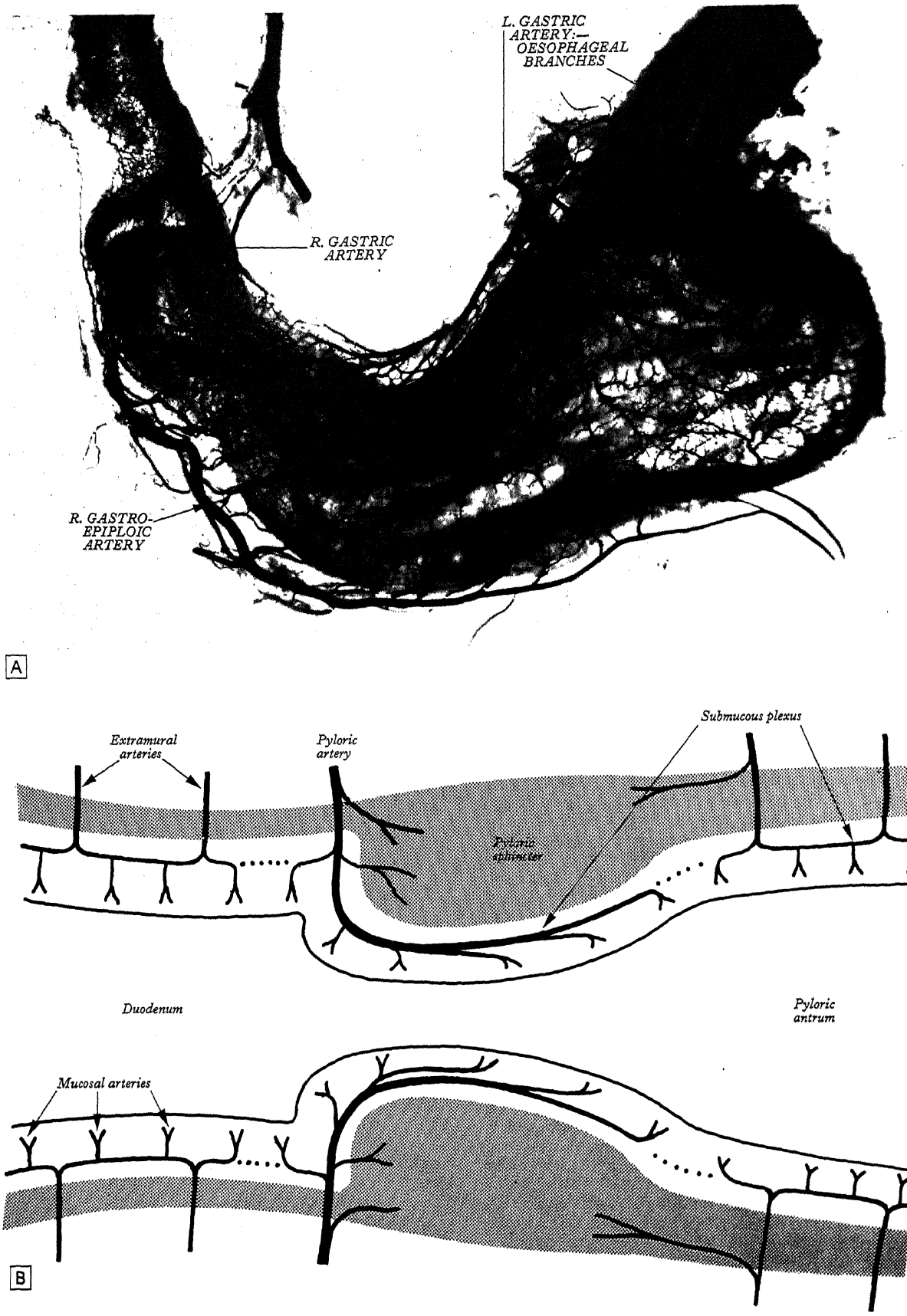
The extent of lateral anastomosis between arteriolar territories in the mucosa is a matter of some debate; Piasecki et al (1989) found that in guinea pigs, ligation of single mucosal arterioles led to full thickness ulceration, indicating that they are end-arterioles, although this condition has not yet been confirmed in humans. These considerations are of course relevant to the formation and growth of gastric ulcers. The dynamic behaviour of the microvasculature is regulated by various neural and paracrine factors which increase mucosal perfusion with the intake of food into the stomach, due to vagal stimulation and the release of different local regulatory factors such as prostanoids, nitric oxide, sensory neuropeptides (e.g. CGRP, SP). Inhibition of endogenous vasodilators, especially the prostanoids e.g. by aspirin, may lead to local ischaemia, ulceration and haemorrhage (Whittle 1986).

GASTRIC NERVES

Innervation arises from several sources (Kyösola et al 1980). The *sympathetic supply* is mainly from the coeliac plexus through its extensions around the gastric and gastro-epiploic arteries. Some rami from the hepatic plexus reach the lesser curvature between the layers of the hepatogastric ligament (p. 1741). Branches from the left phrenic plexus pass to the cardiac end of the stomach, as does one from the left phrenic branch to the right crus of the diaphragm. Inconstant gastric branches come from the left thoracic splanchnic nerves and the thoracic and lumbar sympathetic trunks.

The *parasympathetic supply* is from the vagus nerves (Mackay & Andrews 1983) (p. 1253). Usually one or two rami branch on the anterior and posterior aspects of the gastro-oesophageal junction; the anterior nerves are mostly from the left vagus and the posterior from the right vagus, emerging from the oesophageal plexus. The anterior nerves supply filaments to the cardiac orifice and divide near the oesophageal end of the lesser curvature into branches:

- The *gastric branches* (4–10) radiate on the anterior surface of the body and fundus; one, larger than the others, lies in the lesser omentum near the lesser curvature (*greater anterior gastric nerve*).
- The *pyloric branches*, generally two, one of which traverses the lesser omentum almost horizontally to the right, towards its free edge, then turns down on the left side of the hepatic artery to reach the pylorus, while the other, usually arising from the greater anterior gastric nerve, passes obliquely to the pyloric antrum.



12.96 Blood supply of the stomach and the proximal duodenum. A. Arterial system in a fetal human stomach. The muscle layer has been removed. Note double arcade along the lesser curvature. The arteries have been injected with a mixture of 2% gelatin and India ink and subsequently cleared by the Spalteholz technique. Magnification ×6. B. A scheme of arterial arrangements at the gastroduodenal junction. Dotted lines indicate sites where the submucous plexus may be deficient in continuity. Shaded areas represent the muscular layer of the visceral wall. By courtesy of C Plasecki, Department of Anatomy, Royal Free Hospital School of Medicine, London and the *Journal of Anatomy*.

The posterior nerves produce two groups of branches, gastric and coeliac:

- *Gastric branches* radiate over the posterior surface of the body and fundus and extend to the pyloric antrum but do not reach the pyloric sphincter; the largest (*greater posterior gastric nerve*) passes posteriorly along the lesser curvature, giving branches to the *coeliac plexus*.
- *Coeliac branches*, larger than the gastric, pass in the lesser omentum to the coeliac plexus.

occur on either the anterior or posterior gastric surfaces, but they do in the submucosa and between the layers of the muscularis externa. The latter corresponds to the myenteric (Auerbach's) plexus and contains many neurons. They distribute many axons containing a variety of neurotransmitters and neuromodulators (Burnstock 1986) and also sensory and sensorimotor fibres to the muscular tissue and the mucosa.

The vagus has both secretory and motor effects on the stomach; vagal stimulation evokes a secretion rich in pepsin and increases gastric motility; after vagotomy the stomach is flaccid and empties only slowly. The sympathetic nerve supply is vasomotor to the gastric blood vessels and visceral sensory fibres running within sympathetic nerve trunks provide the main pathway for gastric pain.

SMALL INTESTINE

The small intestine, a coiled tube, extends from the pylorus to the ileocaecal valve, where it joins the large intestine. It is usually said to be 6–7 m long, gradually diminishing in diameter towards its termination. However, it is longer after death owing to the loss of muscle tone; its average length in living adults is perhaps about 5 m (see below). In 109 adult subjects shortly after death it ranged from 3.35–7.16 m in women and from 4.88–7.85 m in men, the average being 5.92 m in women and 6.37 m in men (Underhill 1955). Length was correlated with the height of the individual but was independent of age; the large intestine was much more constant in length. Jit and Grewal (1975), reviewing the topic, reported findings in 137 Indian subjects confirming these associations with height and noting lack of a correlation with weight. They observed that fixation in formalin caused contraction which sometimes reached 44%. Various observers have also passed flexible tubes through the alimentary tract, recording total lengths of 2.7–4.5 m (see Jit & Grewal 1975).

The small intestine occupies the central and lower parts of the abdominal cavity, usually within the colonic loop; it is related in front to the greater omentum and abdominal wall; a portion may reach the pelvis in front of the rectum. It consists of a short, curved sessile section, the *duodenum*, and a long, greatly coiled part attached to the posterior abdominal wall by the mesentery (p. 1743), the proximal two-fifths being the *jejunum*, the distal three-fifths the *ileum*.

DUODENUM (12.97–99)

The duodenum is 20–25 cm long (12 in, hence the name) and is the shortest, widest and most sessile part of the small intestine. It has no mesentery, and is thus only partially covered by peritoneum. It is constantly curved in an incomplete circle, enclosing the head of the pancreas. It is situated entirely above the level of the umbilicus. Arising from the pylorus, it passes backwards, up and to the right for about 5 cm, inferior to the posterior part of the quadrate lobe, to the neck of the gallbladder; its direction varies slightly according to the distension of the stomach. It then curves abruptly (*superior duodenal flexure*) to descend about 7.5 cm anterior to the medial part of the right kidney, usually to the level of the lower border of the third lumbar vertebral body, just medial to the lateral plane (**12.98**). At a second bend (*inferior duodenal flexure*), it turns horizontally left across the vertebral column for about 5–10 cm, just above the umbilical level, with a slight upward slope; it then ascends in front and to the left of the abdominal aorta for about 2.5 cm, ending opposite the second lumbar vertebra in the jejunum. At this union it turns abruptly forwards; this *duodenojejunal flexure* is about 2.5 cm left of the midline and 1 cm below the transpyloric plane. For descriptive purposes it is hence divided into parts: first (superior), second (descending), third (horizontal) and fourth (ascending).

Duodenal relations

Superior (first) part. About 5 cm long, it is the most mobile section, extending from the pylorus to the neck of the gallbladder. Peritoneum covers its anterior aspect but it is bare of this posteriorly, except for about 2.5 cm near the pylorus where it takes a small part in the formation of the anterior wall of the omental bursa; here the lesser omentum is attached to its upper border and the greater omentum to its lower (proximal half). It is related above and in front with the quadrate lobe of the liver and gallbladder and more posteriorly above with the epiploic foramen, behind with the gastroduodenal artery, bile duct and portal vein and posteroinferiorly with the head and neck of the pancreas. It is usually stained by leakage of bile after death especially on its anterior surface where it is related to the gallbladder.

Descending (second) part. From 8–10 cm long, it descends from the neck of the gallbladder along the right side of the vertebral column to the lower border of the third lumbar vertebral body. Crossed by the transverse colon, it is connected to it by some loose connective tissue and above and below this attachment it is covered in front with peritoneum. It is related in front, from above downwards: to the right lobe of the liver, transverse colon and the root of its mesocolon and to the jejunum; behind it is variably related to the right kidney near its hilum (being connected to it by loose connective tissue) to the right renal vessels, the edge of the inferior vena cava and psoas major. Medial to it are the head of the pancreas and bile duct, while lateral is the right colic flexure. A small part of the pancreatic head is sometimes embedded in the duodenal wall. The bile and pancreatic ducts come into contact at its medial side, entering its wall obliquely and uniting to form the *hepatopancreatic ampulla* (p. 1810). The narrow, distal end of this opens on the summit of the *major duodenal papilla*, sited posteromedially in the descending duodenum (**12.99, 134**), 8–10 cm distal to the pylorus. An accessory pancreatic duct may open about 2 cm above to the major papilla on a *minor duodenal papilla*.

Horizontal (inferior or third) part. About 10 cm long, this passes from the right of the lower border of the third lumbar vertebra, sloping slightly up and to the left across the inferior vena cava, to end in the fourth part in front of the abdominal aorta. Its anterior surface is crossed with peritoneum, except in the median plane where it is crossed by the superior mesenteric vessels and mesenteric root. Its posterior surface is covered by peritoneum only at its left end, where the left layer of the mesentery sometimes covers it. The posterior surface rests upon: the right ureter, right psoas major, right testicular (or ovarian) vessels, the inferior vena cava and the abdominal aorta (with the origin of the inferior mesenteric artery). Its superior aspect is related to the head of the pancreas, its inferior to coils of the jejunum.

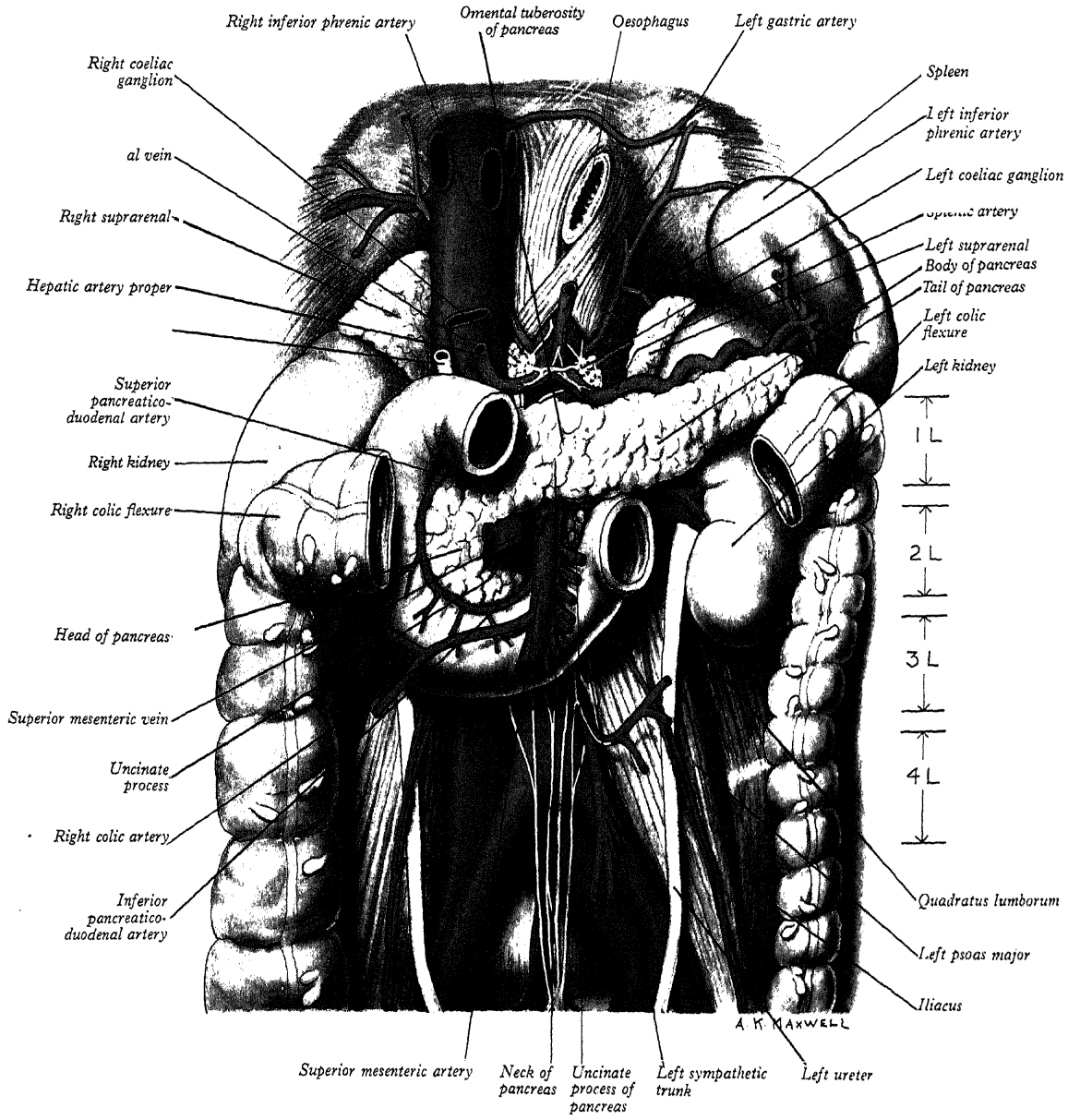
Ascending (fourth) part. About 2.5 cm long, it ascends on or immediately to the left of the aorta, to the level of the upper border of the second lumbar vertebra, where it turns forwards into the jejunum at the *duodenojejunal flexure*; it is anterior to the left sympathetic trunk, left psoas major, left renal and gonadal vessels and the inferior mesenteric vein. To the right it gives attachment to the upper part of the root of the mesentery, its left layer being continued over the duodenum's anterior surface and left side. To its left are the left kidney and ureter; above is the body of the pancreas; in front are the transverse colon and transverse mesocolon, the latter separating the duodenojejunal flexure from the omental bursa and stomach.

Peritoneal attachments

The superior part of the duodenum is slightly mobile, while the rest is almost fixed, being sessile upon neighbouring structures. Radiologically, after a barium meal, the superior part appears as a triangular, homogeneous shadow, the 'duodenal cap' (**12.92, 93**).

The terminal part and the duodenojejunal flexure are said to be positioned by the '*suspensory muscle of the duodenum*' (suspensory muscle, or ligament, of Treitz), often described as being in two parts:

- a slip of *skeletal* muscle derived from the diaphragm near its oesophageal opening, ending in connective tissue near the coeliac artery
- a fibromuscular band of *smooth* muscle, passing from the



12.97 Dissection to show the duodenum, pancreas, major arterial trunks of the gastrointestinal tract and surrounding structures. The right and left hepatic veins have been cut away at their points of entry into the inferior vena cava. The superior hypogastric plexus is shown in front of the sacral promontory and the sympathetic nerves which form it are seen descending across the bifurcation of the aorta, the left common iliac vein and the body of the fifth lumbar vertebra. (In this specimen the left renal artery is situated anterior to the left renal vein at the hilum of the kidney.)

duodenum (third and fourth parts and duodenojejunal flexure) to blend with the same pericoeliac connective tissue.

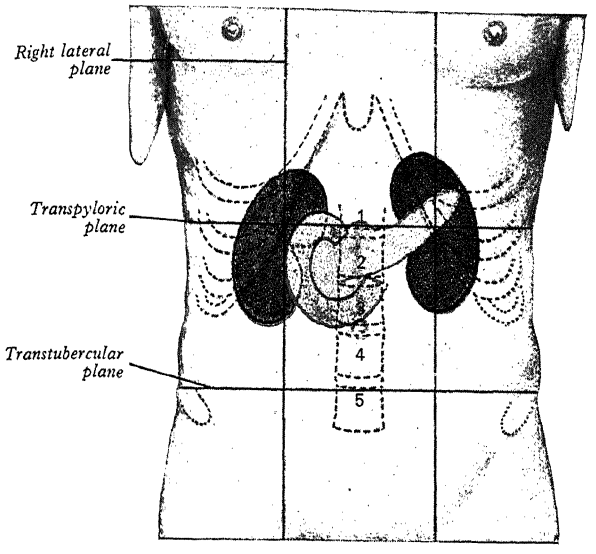
Treitz (1853) described both entities, naming the former *der Hilfsmuskel* (the accessory muscle). Subsequent authorities (Low 1907) regarded them as a digastric muscle, naming the whole the suspensory **muscle** of Treitz, a misnomer perpetuated in most textbooks. Confusion was increased by Haley & Peden (1943), who derived the 'suspensory muscle' from the right crus, and by Argème et al (1970), who described an intermediate tendon but regarded this as part of a 'false' digastric muscle. Jit (1952, 1977) has persistently repeated the dual nature of the original description by Treítz, supporting it by embryological and histological evidence. The diaphragmatic slip (Hilfsmuskel) has no satisfactory official name. It is supplied, according to Jit, by myelinated nerve fibres probably from the phrenic nerve (pp. 816, 1265) and is sometimes considered an aberrant part of iliocostalis thoracis. The suspensory muscle proper (smooth muscle) is supplied by autonomic fibres from the coeliac and superior mesenteric plexuses (Jit & Grewal 1977). Descriptions of the duodenal attachments of the muscle vary; none of these accounts contain a convincing view of its function, the usual suggestion being that it augments duodenojejunal flexure, acting like a valve.

Vessels and nerves

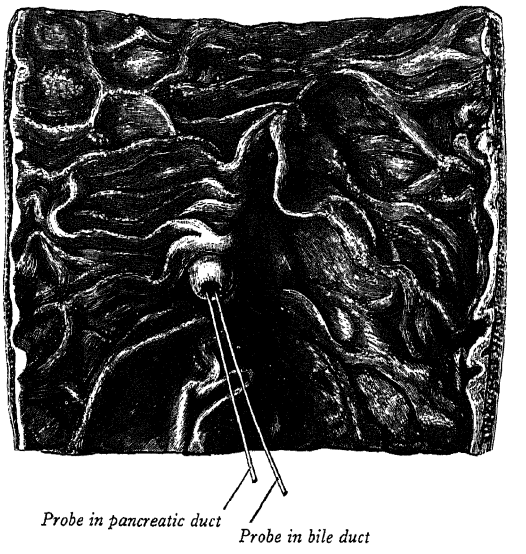
Arteries supplying the duodenum. Arising from the right gastric, supraduodenal, right gastro-epiploic and superior and inferior pancreaticoduodenal arteries (pp. 1549, 1553) the first (superior) part receives two leashes of small rami, one from the hepatic artery proper and one from the gastroduodenal artery. These branches also supply the adjacent pyloric canal, with some anastomosis in the muscular layer across the pyloroduodenal junction.

Veins. These end in the splenic, superior mesenteric and portal veins.

Microvasculature. The mucosa has a rich supply of microvessels, arranged so as to enhance the accumulation of bicarbonate near the



12.98 Surface projection of the duodenum, pancreas and kidneys on the anterior wall of the trunk. The lumbar vertebrae are numbered.



12.99 Interior of the descending (second) part of the duodenum, showing the major duodenal papilla.

mucosal surface, and so protect it against gastric acid by bicarbonate secretion from the surface epithelium.

Nerves. They come from the coeliac plexus.

JEJUNUM AND ILEUM

The rest of the small intestine extends from the duodenojejunal flexure to the ileocaecal valve, ending at the junction of the caecum and ascending colon. It is arranged in a series of coils attached to the posterior abdominal wall by the mesentery. It is completely covered by peritoneum, except along its mesenteric border where the two mesenteric layers diverge to enclose it. Its proximal two-fifths is the *jejunum*, the rest the *ileum*; the division is arbitrary, as the character of the intestine changes only gradually, but samples from these two 'parts' show characteristic differences.

Jejunum

The jejunum, with a diameter of about 4 cm, is thicker walled, redder in life and more vascular. Its circular mucosal folds (see below) are large and frequent and its villi larger. Aggregated lymphatic follicles (p. 1771) are almost absent from the proximal (upper) jejunum; distally they are still fewer and smaller than in the ileum and are often discoidal. The circular folds can be felt through its wall and, since they are absent from the distal ileum, palpation allows a crude distinction between upper and lower intestinal levels. The jejunum lies largely in the umbilical region but may extend into surrounding areas. The first coil occupies a recess between the left part of the transverse mesocolon and the left kidney.

Ileum

The ileum has a diameter of 3.5 cm; its wall is thinner than in the jejunum. A few circular folds occur proximally but these are small and disappear almost entirely in its distal part. Aggregated lymphatic follicles are, however, larger and more numerous than in the jejunum. The ileum is mainly in the hypogastric (pubic) and pelvic regions. Its terminal part usually lies in the pelvis, from which it ascends over the right psoas major and right iliac vessels to end in the right iliac fossa, opening into the medial side of the junction between the caecum and colon.

The fan-like mesenteric attachment of the jejunum and ileum to the posterior abdominal wall allows free movement, each coil adapting to changes in form and position.

The mesentery

The mesentery (p. 1742), like a complex fan, has a root, about 15 cm long, attached to the posterior abdominal wall along a line running diagonally from the left side of the second lumbar vertebral body to the right sacro-iliac joint, crossing successively: the horizontal part of the duodenum, aorta, inferior vena cava, right ureter and right psoas major (**12.76**). Its average breadth from its root to the intestinal border is about 20 cm, but is greater at intermediate levels. Its two peritoneal layers contain: the jejunum, ileum, jejunal and ileal branches of the superior mesenteric vessels, nerves, lacteals and lymph nodes, together with a variable amount of fat.

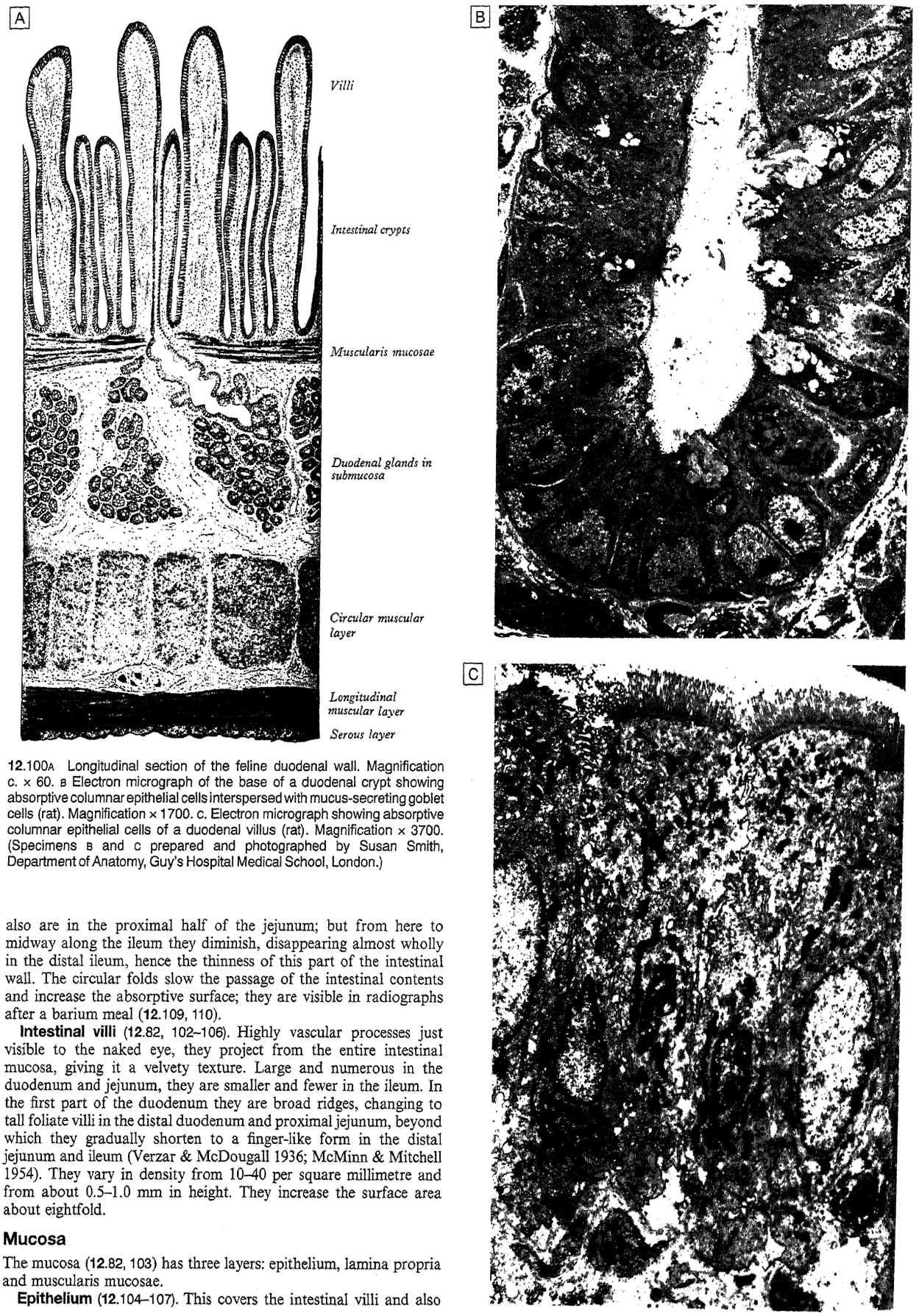
Ileal diverticulum

The ileal diverticulum (of Meckel) projects from the antimesenteric border of the distal ileum in about 3% of subjects, its average position being about 1 m above the ileocaecal valve and its average length about 5 cm. Its calibre is like that of the ileum, its blind extremity being free or connected with the abdominal wall or some other part of the intestine by a fibrous band. It represents the vitelline (yolk) duct's persistent proximal part; its mucosa is ileal in type but small areas may have a gastric structure, with oxyntic cells secreting acid. Sometimes heterotopic areas of pancreatic or other tissues occur in its wall. In a study of 1816 late fetal and neonatal cadavers Miyabara et al (1974) found a diverticulum in 61 individuals (3.4%). Of these, gastric mucosa was present in 11, jejunal mucosa in two, colonic mucosa in two and pancreatic tissue in one.

MICROSTRUCTURE OF SMALL INTESTINE

The intestinal wall has the usual layers of mucosa, submucosa, muscularis externa and serosa or adventitia (**12.82**, 100, 102–109). The mucosa is thick and very vascular in the proximal small intestine, but thinner and less vascular in the distal. In part of its course it is ridged by the underlying submucosa to form *circular folds*, and the whole surface is covered by mucosal finger- or leaf-like *intestinal villi*. Between the bases of the villi are numerous simple tubular *intestinal glands*, while in the duodenum there are also *submucosal glands*.

Circular folds (plicae circulares or 'valves' of Kerkring (**12.101**). These are large, crescentic folds of mucosa which project into the intestinal lumen transversely or slightly obliquely to the long axis. Unlike gastric folds they are not obliterated by distension of the intestine. Most extend round half or two-thirds of the luminal circumference; some are complete circles, some bifurcate and join adjacent folds, some are spiral but extend little more than once round the lumen, though occasionally two or three times. Larger folds are about 8 mm deep at their broadest, but most are smaller than this, and larger folds often alternate with smaller ones. Plicae begin to appear about 2.5–5 cm beyond the pylorus. Distal to the major duodenal papilla they are large and close together, as they



12.100A Longitudinal section of the feline duodenal wall. Magnification c. x 60. B Electron micrograph of the base of a duodenal crypt showing absorptive columnar epithelial cells interspersed with mucus-secreting goblet cells (rat). Magnification x 1700. C. Electron micrograph showing absorptive columnar epithelial cells of a duodenal villus (rat). Magnification x 3700. (Specimens B and C prepared and photographed by Susan Smith, Department of Anatomy, Guy's Hospital Medical School, London.)

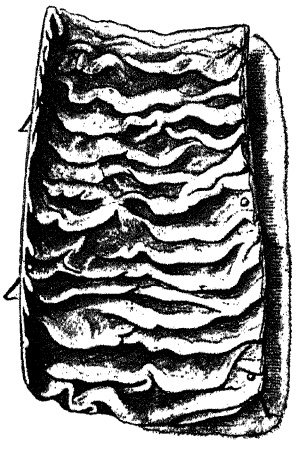
also are in the proximal half of the jejunum; but from here to midway along the ileum they diminish, disappearing almost wholly in the distal ileum, hence the thinness of this part of the intestinal wall. The circular folds slow the passage of the intestinal contents and increase the absorptive surface; they are visible in radiographs after a barium meal (**12**.109, 110).

Intestinal villi (**12**.82, 102–106). Highly vascular processes just visible to the naked eye, they project from the entire intestinal mucosa, giving it a velvety texture. Large and numerous in the duodenum and jejunum, they are smaller and fewer in the ileum. In the first part of the duodenum they are broad ridges, changing to tall foliate villi in the distal duodenum and proximal jejunum, beyond which they gradually shorten to a finger-like form in the distal jejunum and ileum (Verzar & McDougall 1936; McMinn & Mitchell 1954). They vary in density from 10–40 per square millimetre and from about 0.5–1.0 mm in height. They increase the surface area about eightfold.

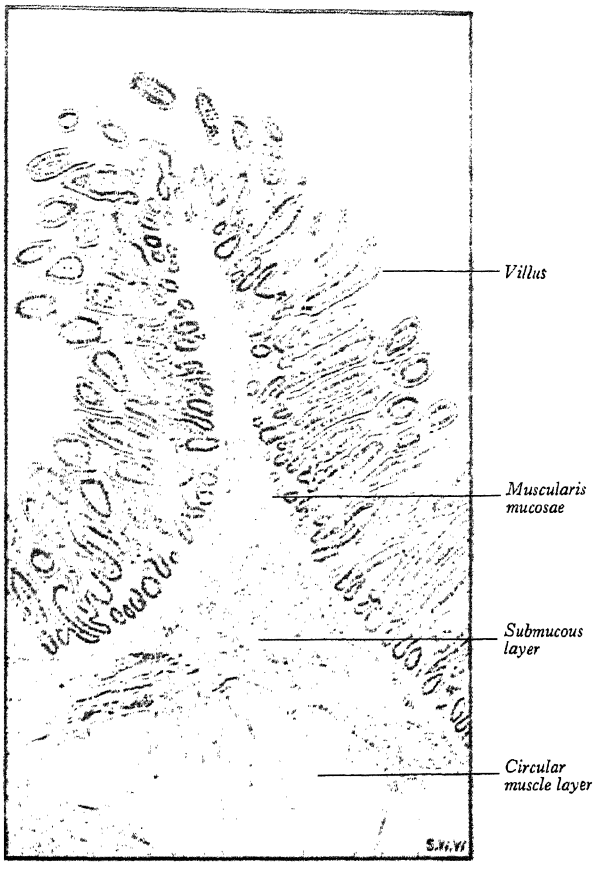
Mucosa

The mucosa (**12**.82, 103) has three layers: epithelium, lamina propria and muscularis mucosae.

Epithelium (**12**.104–107). This covers the intestinal villi and also



12.101 Internal aspect of a representative sample of the proximal jejunum, showing circular folds.



12.102 Section through a circular fold from the human small intestine. Stained with haematoxylin and eosin. Magnification x 19.

the intestinal glands (crypts) which discharge their contents between the bases of villi. Covering the surfaces of the villi are two types of cell, *enterocytes* and *goblet* cells. In localized areas covering lymphoid tissues, another type, the *microfold cell* (*M cell*) is also present in smaller numbers.

These various cell types rest on a basal lamina to which they adhere. Although this is too thin to be resolved by light microscopy, its position is marked by a thicker, periodic acid–Schiff (PAS) stainable layer, mostly of connective tissue matrix, the basement membrane (see p. 87).

Enterocytes. These are absorptive columnar cells, prismatic in shape and about 20 μm tall (**2.00**, **12.100c**, 108, 109). They are much the more numerous class of cell in the intestinal lining, and are the site of nutrient absorption. Their surfaces bear up to 3000 microvilli which are collectively though not individually visible by light microscopy as a striated border about 1 μm thick (p. 40). (**2.24**, **12.108**). By light microscopy the cytoplasm appears rather granular, and the vertically elongate nucleus is quite euchromatic, and placed a little below the centre of the cell. Electron microscopy shows enterocytes to be rich in organelles, as might be expected of such active cells.

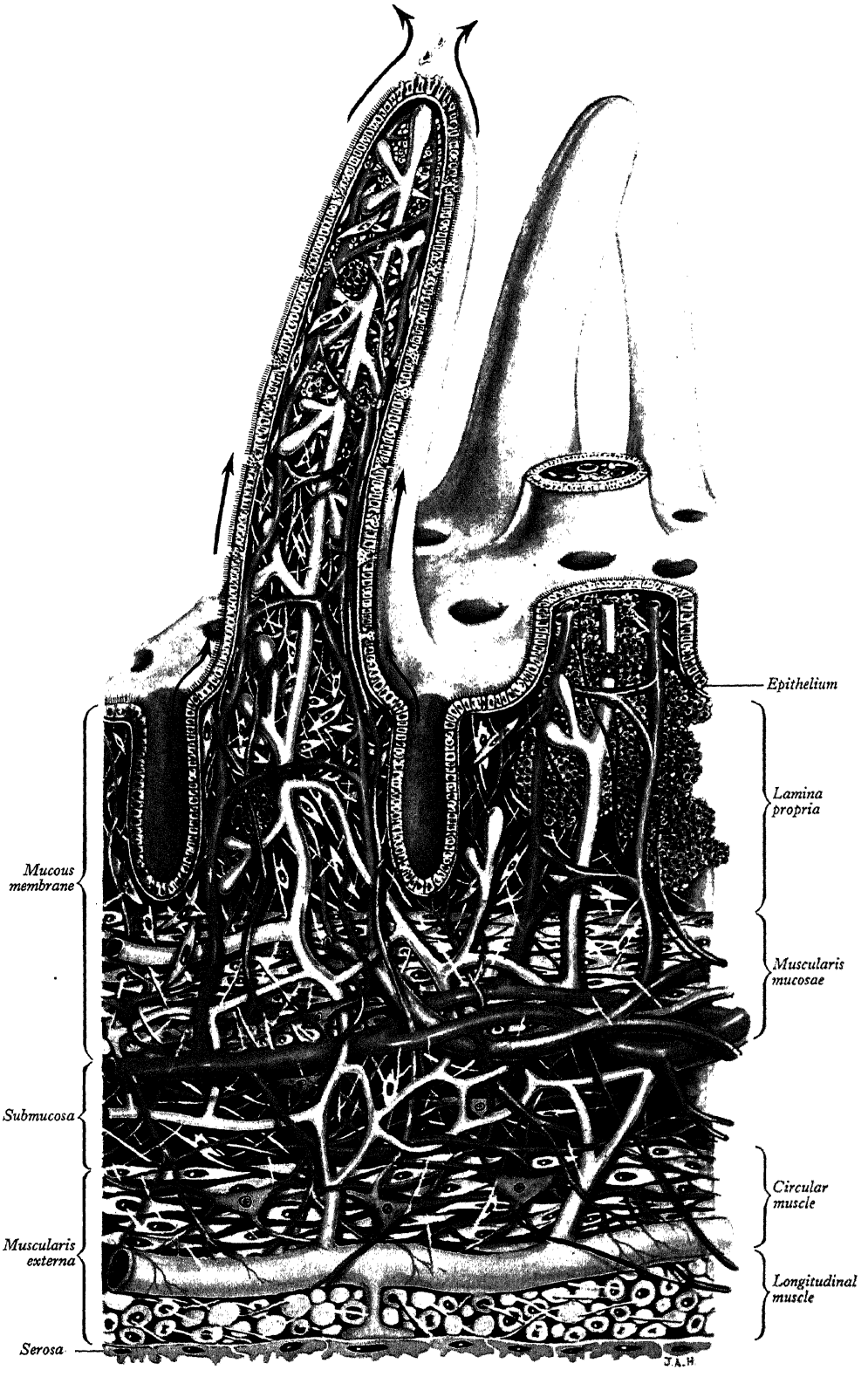
Because of its importance in nutrition, and the relative ease with which it can be isolated for experiments, the striated border has been the subject of considerable research. Electron microscopy shows it to be composed of multitudes of parallel cylindrical microvilli, each about 1 μm long and 0.1 μm broad. On the external surface of the microvillar plasma membrane is a thick glycocalyx (p. 24) composed of fine perpendicular filaments, the glycosylated terminals of membrane proteins. These are particularly long at the tips of microvilli, and collectively form a thick (up to 0.5 μm) stratum over the surface of the striated border. The glycocalyx is resistant to protease attack and is thought to protect the underlying epithelium against pancreatic enzymes in the intestinal lumen. It also serves to adsorb a number of such enzymes so that there is a zone of digestion of food close to the site of absorption. In the cytoplasmic core of each microvillus are fine actin filaments basally continuous with a plexiform sheet of similar filaments, the terminal web, lying across the cell's apical cytoplasm (**2.23**, **12.109**). Myosin I and other actin-binding proteins also participate in forming these arrays, serving to form a firm anchorage, and perhaps to institute changes in cell shape under some circumstances (see below). The ultrastructural details of microvillar organization are further described on page 40.

Within the general cytoplasm, rod-shaped mitochondria are numerous, indicating that absorption requires much chemical energy on the part of the enterocyte. There is also copious agranular endoplasmic reticulum which, amongst other functions, bears enzymes for synthesizing lipid from the fatty acids and glycerol absorbed by the striated border. There are also some granular endoplasmic reticulum and free ribosomes; the Golgi apparatus is supranuclear and the apical region, beneath the terminal web, contains numerous lysosomes and endocytic vesicles as well as microtubules and a centriole pair (p. 43).

Enterocyte structure varies with their position on the villus, reflecting the stage in the cycle of differentiation and replacement by stem cell mitosis (see below). At the summits of intestinal villi they undergo programmed, apoptotic cell death, during which process their cytoplasm becomes darkly stained and their microvilli stunted and degenerate before the cell finally disintegrates. Changes in the microvillous surface area have also been shown to occur during the reproductive cycle (in female rats) and during ageing (Penzes & Regius 1985).

The luminal surface is an important barrier to diffusion, so that nutrients generally have to pass through enterocytes (*transcellular absorption*) before they can reach the underlying tissues. Classical junctional complexes (p. 28) surround the polygonal apices of enterocytes, their tight junctions forming an effective diffusion barrier. However, when some nutrients, e.g. glucose, are in high luminal concentrations, extensive leakage may occur through intercellular junctions (*paracellular absorption*), perhaps assisted by contraction of the cell web; this may also be a route for transepithelial absorption of antibodies in certain cases, e.g. in premature babies. Further basally, the lateral walls of enterocytes are highly folded, interdigitating with each other to form complicated intercellular boundaries, anchored periodically by desmosomes and making contact at gap junctions.

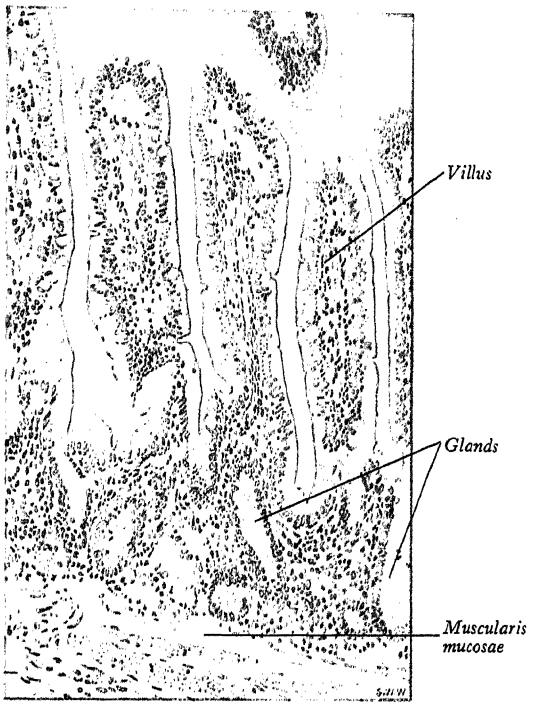
The roles of these cells in digestion and absorption have attracted much attention. The absorption of amino acids and simple carbohydrates is probably facilitated by diffusion across cell membranes, materials traversing the cells to subjacent capillary arrays in the lamina propria. Lipid absorption appears to be by diffusion of small molecules (fatty acids, etc.) through the luminal membrane, the lipid accumulating in vacuoles in the apical cytoplasm, before being discharged into the lateral and basal intercellular spaces and thence to the subjacent lymphatics. Examination of striated borders isolated



12.103 A three-dimensional reconstruction of the architecture of the intestinal villi and subjacent wall (the principal layers of the latter are indicated): arteries and arterioles (red), veins and venules (blue), central lacteals and other lymphatic channels (orange), aggregations of lymphocytes (yellow), neural elements (green), non-striated muscle fibres (magenta), fibroblasts (white). Note the orifices of the intestinal crypts (of Lieberkühn). Types of cells in the epithelium include absorptive cells, goblet cells and entero-endocrine cells. Arrows indicate the direction of cell migration. The various layers are not drawn to scale.

by fractionation and centrifugation has shown that enzymes such as disaccharidases are bound to their surfaces, where much intestinal digestion may occur, perhaps in the cell coat in close proximity to the site of absorption. Although most of these enzymes are derived from the pancreas, some disaccharidases are synthesized by the enterocytes themselves, as shown by the demonstration of mRNA for this enzyme by in situ hybridization.

Mucous (goblet) cells. These have elongated, basal nuclei and an



12.104 Intestinal glands and villi in the human small intestine. Stained with haematoxylin and eosin. Magnification × 120.

12.105 Light micrograph of part of the mucosa of the murine small intestine, showing a villus in longitudinal section. Non-striated myocytes (pink) can be seen in the lamina propria of the villus. Their contraction has caused the villus to shorten, so that its surface is folded into a series of ridges and grooves (compare **12.**106). Stained with haematoxylin, eosin, and periodic acid/Schiff. Magnification × 250. (Prepared and photographed by Stephen Sitch, Department of Anatomy, Guy's Hospital Medical School, London.)

apical region containing many membrane-bound mucin granules (**12.**108A). When tissues are fixed in formalin, and also many other fixatives, these granules swell rapidly to produce the characteristic but artefactual goblet-like shape. When fixed more rapidly, e.g. by quick freezing, they are more columnar or conical in form. Their apical surface bears a few short microvilli, and in the supranuclear region there is a prominent Golgi apparatus, with granular endoplasmic reticulum more basally situated. Their secretions are important in the chemical and mechanical protection and lubrication of the intestinal wall, and also in its immune defence, since class IgA antibodies are also secreted; at their bases and sides the goblet cells endocytose IgA originally secreted by B lymphocytes present in the underlying lamina propria, and this provides a major source of protection against microbial organisms in the gut lumen.

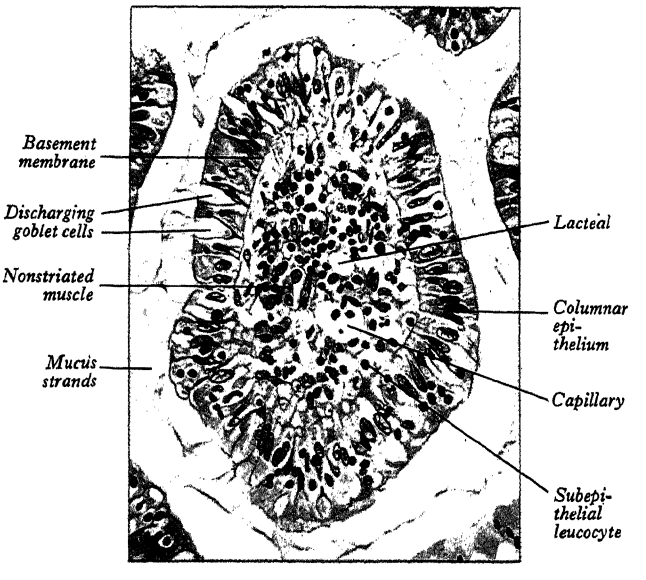
Microfold cells. They are present where the epithelium covers masses of lymphoid tissue in the intestinal wall. They have long, rather widely spaced microvilli between which are numerous endocytic vesicles. They are thought to transfer antigens from the lumen of the intestine to the underlying tissues, acting as a sampling system to enable the lymphoid tissue to produce appropriate antibodies for secretion (Owen & Nemanic 1978). Further details are given on page 78.

Lymphocytes. These are also present between the basal regions of the epithelial cells (**12.**108). They are migratory cells derived from the underlying lymphoid tissue and constitute an important means of defence against viral attack, and against the proliferation of cancerous cells (see p. 1423 et seq).

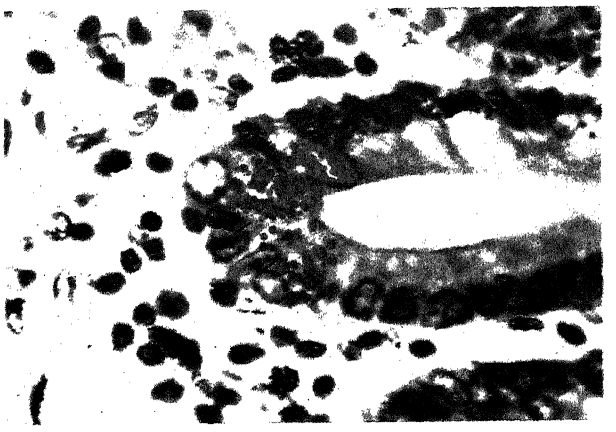
Intestinal glands or intestinal crypts (of Lieberkühn). Numerous throughout the intestinal mucosa (**12.**82, 100A, 103, 104, 106), they are tubular, perpendicular pits, opening at small circular apertures between the bases of the villi. Their thin walls consist of columnar epithelium bounded externally by a basement membrane, associated with which is a rich capillary plexus. The epithelium consists of mucous cells, Paneth cells, stem cells and enteroendocrine cells.

Mucous cells. These are similar to the goblet cells of the villi.

Paneth cells. Numerous in the deeper parts of the intestinal crypts, particularly in the duodenum, they are rich in zinc and contain large acidophilic granules (**12.**107) staining with, e.g. eosin, and phosphotungstic haematoxylin. Electron microscopy shows irregular apical microvilli and prominent membrane-bound vacuoles containing a granular matrix with crystalline inclusions in the



12.106 Transverse section through a villus in the human jejunum. Stained with haematoxylin and eosin. Magnification × 380.



12.107 Part of a transverse section of the ileum, showing zymogenic (Paneth) cells containing orange-stained zymogen granules at the base of an intestinal gland. 'Undifferentiated' epithelial cells are also visible. Mallory's azan stain. Magnification × 400.

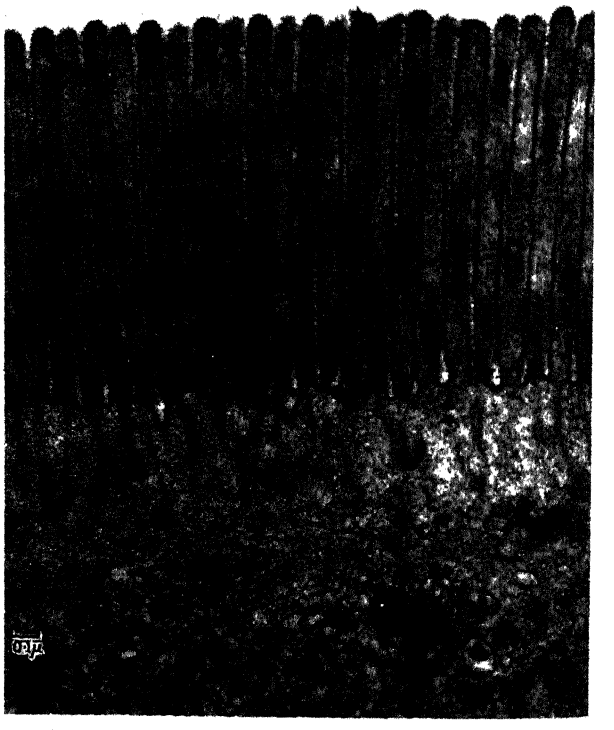
supranuclear cytoplasm. These vacuoles are PAS positive and they contain some carbohydrate. Scattered mitochondria, lysosomes and much granular endoplasmic reticulum are present, especially in the basal region. The functions of these cells are not certain, but there is evidence that they secrete lysozyme, an antibacterial substance, and also that they can phagocytose luminal particles. For further details see Rodning et al (1982).

Stem cells. The most numerous cells; they occur in a zone occupying the middle region of the crypts, and provide the source of most of the cell types of the intestinal epithelium. They proliferate by mitotic division, their progeny ascending out of the intestinal glands along the sides of the villi, where they differentiate into columnar or goblet cells; eventually they reach the apices of villi and are shed or die and disintegrate in situ as a result of apoptosis. Thus the villous epithelium is continually renewed. The apical surfaces of these cells, when not dividing, have fewer and more irregular microvilli than do the columnar cells, with occasional pseudopodia. Their lateral plasma membranes are smooth, but intercellular junctions are similar in both types of cell. Their nuclei are basal and the terminal webs poorly developed. Membrane-bound secretory granules are believed to be discharged by both apocrine and merocrine methods. These cells multiply at the rate of 1 cell per 100 per hour, one of the most rapid proliferation rates in the body (Lipkin et al 1963; MacDonald et al 1964).

Enteroendocrine cells. Scattered among the walls of the intestinal glands, and less commonly over the villi, they are of several types, secreting bioactive peptides and bioamines at their bases into the surrounding lamina propria. For further details see page 1787.

Lamina propria. This is composed of connective tissue, providing

A



12.108A Transmission electron micrograph of the columnar epithelium lining the murine small intestine, showing a mucus-secreting goblet cell between two absorptive cells which bear microvilli. The cells rest on a delicate basal lamina deep to which is the vascular lamina propria. Magnification × 4800. (Prepared and photographed by Derrick J Lovell, Department of Anatomy, Guy's Hospital Medical School, London.)

12.108B Electron micrograph of the apical region in a columnar cell from the jejunum (rat) showing the regular series of microvilli which constitutes the striated border of light microscopy. Microfilaments can be seen passing from the microvilli to the terminal web. Magnification *c.* × 32 500.

mechanical support for the epithelium: it has a rich vascular plexus, receiving absorbed nutrients from the enterocytes, and forms the cores of the villi. It also contains lymphoid tissue, fibroblasts and connective tissue fibres, smooth muscle cells, eosinophilic leucocytes, macrophages, mast cells, capillaries, lymphatic vessels and non-myelinated nerve fibres. Plasma cells are numerous and lymphocytes in many regions are clustered in solitary and aggregated lymphatic follicles (Peyer's patches), some extending through the muscularis mucosae into the submucosa (see below).

Muscularis mucosae. The muscularis mucosae forms the base of the mucosa, with external longitudinal and internal circular layers of smooth muscle cells; it follows the surface profiles of the circular folds and sends slips of smooth muscle cells into the cores of villi.

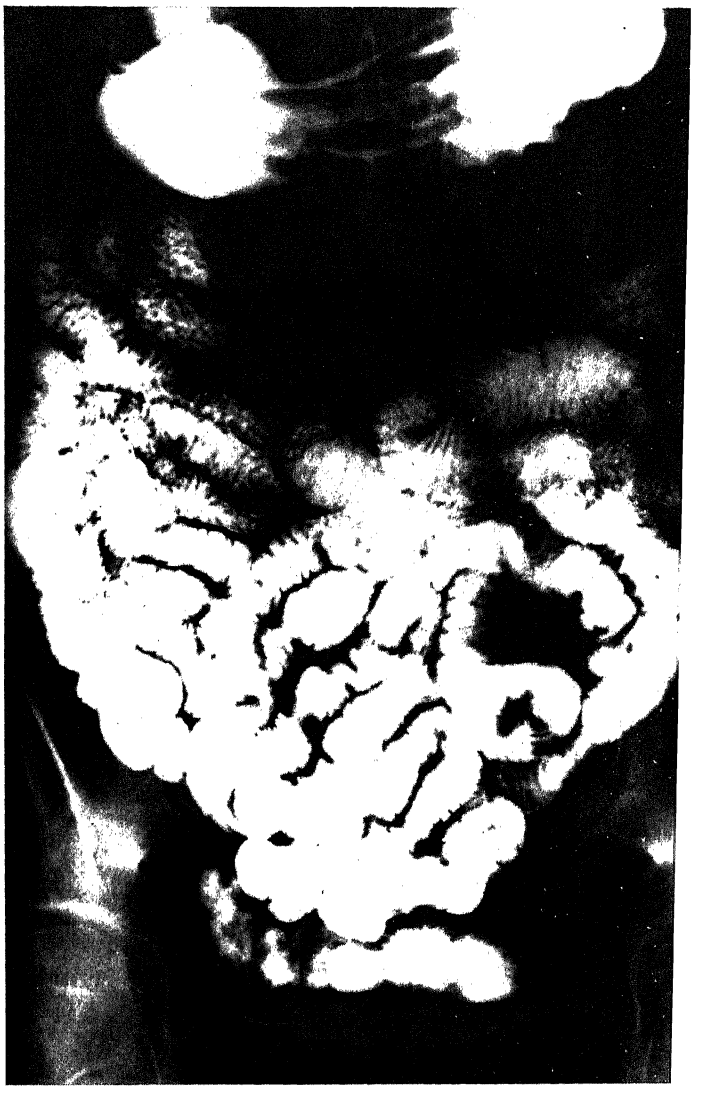
Structure of intestinal villi. A villus has a core of delicate connective tissue containing a large blind-ending lymphatic vessel (lacteal), blood vessels, nerves and smooth muscle cells, covered by columnar epithelium on a basement membrane (**12**.103, 104, 105, 108). The lacteal, which is usually single but occasionally double, starts in a closed, dilated extremity near the villous summit and descends to empty into a narrower lymphatic plexus in the lamina propria. Its wall is a single layer of endothelial cells. Smooth muscle cells derived from the muscularis mucosae cluster around the lacteal from the base to the summit of the villus, some being attached to both the basement membrane of the epithelium and the lacteal. Contraction of these myocytes therefore 'milks' the lacteals, forcing its contents into the underlying lymphatic plexus. Blood vessels form a capillary plexus in the lamina propria, enclosed in fine-fibred connective tissue. These capillaries are lined by fenestrated endothelium, probably to ensure the rapid intake of nutrients diffusing from epithelium (Clementi & Palade 1969).

Mucosa-associated lymphoid tissue. This includes masses of lymphoid tissue situated mainly in the lamina propria, but sometimes expanding into the submucosa. They are the source of B and T lymphocytes and other related cells for the immune defence of the gut wall (for details see p. 1444). Essentially they are comprised of one or more lymphoid *follicles* (centres of B lymphocyte proliferation) and attendant clusters of T-lymphocytes and antigen presenting cells. In the epithelium overlying these structures there are a few specialized microfold (M) cells (see above) which are thought to provide a route for sampling the antigens of the gut lumen. The lymphoid follicles have a rich blood supply, and are the source of efferent lymphatics. Villi are small or absent over the larger of the follicular groups. They can be classified as *solitary* and *aggregated lymphoid follicles*. *Solitary lymphoid follicles* are scattered along the length of the intestinal mucosa, being most numerous in the distal ileum. *Aggregated lymphoid follicles* (*Peyer's patches*, **12**.111) are circular or oval masses containing 10–260 follicles, and varying in length from 2 to 10 cm. Like other masses of mucosa-associated lymphoid tissue (except lymph nodes), solitary and aggregated lymphoid follicles are most prominent around the age of puberty, when they may number up to 300, thereafter diminishing in number and size although many persist into old age (Cornes 1965). Aggregated follicles are largest and most numerous in the ileum, whilst in the distal jejunum they are small, circular and few, and only occasional in the duodenum. They are usually situated in the wall opposite the mesenteric attachment. In typhoid fever follicles may ulcerate, such ulcers being oval, their long axes lying along the gut; hence subsequent fibrosis does not constrict the intestine.

Submucosa

The submucosa is composed of loose connective tissue carrying blood vessels, lymphatics and nerves. Its ridged elevations form the cores of the plicae circulares, and, more generally, the obliquely crossing geometry of its collagen fibres, together with elastin fibres, permits the considerable changes in transverse and longitudinal dimensions which accompany peristalsis, whilst still providing adequate support, elasticity and strength (Gabella 1987).

Submucosal (duodenal) glands (of Brunner). As their name implies, these are limited to the submucosa of the duodenum (**12**.82, 100A, B), their ducts traversing the muscularis mucosae to enter the bases of the mucosal crypts. They are largest and most numerous near the pylorus, and form an almost complete layer in the superior part and proximal half of the descending duodenum. Thereafter they gradually diminish in number and disappear at the duodenojejunal junction. They are small, branched compound acino-tubular glands, each having several acini lined by short columnar epithelial cells and apparently (in humans) containing a single type of mucous secretory cell. The small, basal nuclei of these cells vary during the secretory cycle. The Golgi apparatus is extensive and mucin droplets numerous. Many enteroendocrine cells (see above) are present among the mucinogenic cells. These glands secrete a watery fluid rich in bicarbonate, which helps to neutralize the acid secretions of the stomach as the food enters the duodenum. The cells may also secrete a trypsinogen-activating factor which converts this enzyme to trypsin after secretion from the pancreas.



12.109 Radiograph showing the small intestine, taken during a barium follow-through. The feathery appearance of the profile of the small intestine is due to the plicae circulares; constrictions due to peristalsis can also be seen. (Provided by Shaun Gallagher; photography by Sarah Smith, UMDS, Guy's Hospital Campus, London.)

Muscularis externa

The muscularis externa is thicker in the proximal intestine, consisting of a thin external longitudinal and a thick internal circular layer of smooth muscle cells. For details, see Gabella (1988).

Serosa

The serosa is visceral peritoneum consisting of a subserous stratum of loose connective tissue covered by mesothelium. Where the duodenum becomes retroperitoneal it is mainly covered by a connective tissue adventitia rather than serosa.

12.110 Radiograph showing part of the small and large intestine, taken after the administration of a small bowel enema which outlines the intestine, followed by methyl cellulose which distends it and produces a double contrast image. The plicae circulares are clearly demonstrated by this technique. C = caecum; I = ileum; J = jejunum; PC = plicae circulares; TI = terminal part of ileum. (Supplied by Shaun Gallagher; photography by Sarah Smith, UMDS, Guy's Hospital Campus, London.)

Enteric plexuses. These are present in the wall of the small intestine, as elsewhere in the tract, consisting of two ganglionated strata, the myenteric (Auerbach's) plexus between the two layers of external muscle, and the submucosal (Meissner's) plexus on the submucosal surface of the circular layer of muscle. Numerous axons extend from these to all parts of the wall, providing its motor, sensory and sensorimotor supply (see p. 1749).

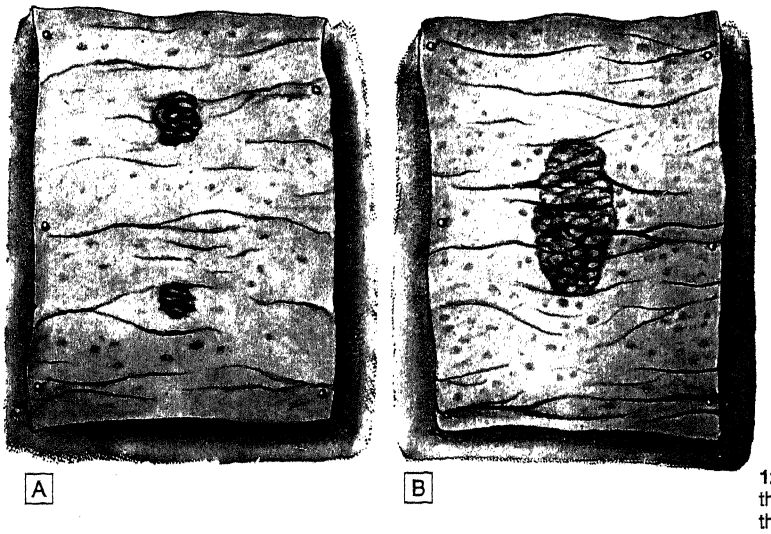
Vessels

Jejunal and ileal arteries (12.112). These stem from the superior mesenteric, branches of which, reaching the mesenteric border, extend between the serosal and muscular layers. From these, numerous branches traverse the muscle, supplying it and forming an intricate submucosal plexus from which minute vessels pass to glands and villi (see p. 1771). Anastomoses between the terminal intestinal arteries are few and alternate vessels are often distributed to opposite sides of the gut. The **veins** follow the arteries. (For a detailed investigation of the distribution and variations in coeliac and superior mesenteric arteries consult Nesebar et al 1969.)

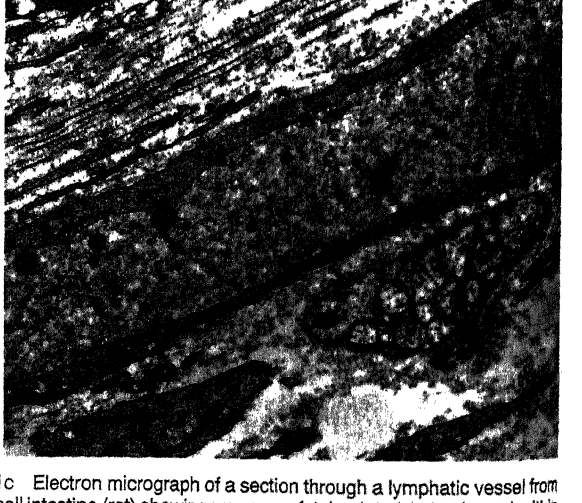
Lymph vessels (lacteals). They are arranged at two levels, one mucosal, the other in the muscular coat. Lymph vessels of villi commence, as described on p. 1771, form an intricate plexus in mucosa and submucosa, are joined by vessels from lymph spaces at the bases of solitary follicles and drain to larger vessels at the mesenteric aspect of the gut. The lymph vessels of the muscular tunic form a close plexus running mostly between the two muscle layers; they communicate freely with mucosal vessels and open like them into the lacteal drainage at the attached border of the gut.

Nerves

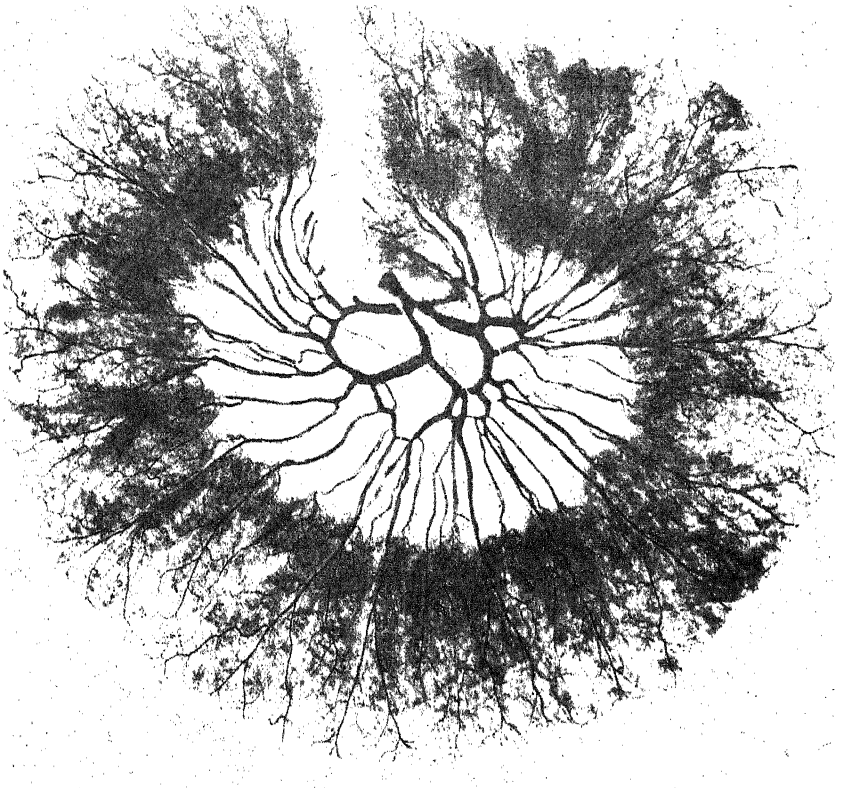
These are supplied from the vagi and thoracic splanchnic nerves through the coeliac ganglia and superior mesenteric plexuses. Fibres pass to the *myenteric plexus* (p. 1749) of nerves and ganglia between the circular and longitudinal layers of the muscularis externa, which they supply. From this a secondary, *submucous plexus* is derived, formed by branches perforating the circular muscular layer; it also contains ganglionic neurons from which fibres pass to the muscularis mucosae and the rest of the mucosa. Nerve bundles in the submucous plexus are finer. Ganglion cells in both plexuses are essentially parasympathetic (vagal). An old controversy on the source of post-ganglionic neurons in the enteric ganglia was renewed by Andrew (1971); endodermal and mesodermal origins have been suggested, but the evidence now indicates the neural crest as their source (see p. 235). In general the sympathetic system inhibits peristalsis but stimulates the sphincters and, muscularis mucosae. The parasympathetic generally augments peristalsis and inhibits the sphincters, the results of parasympathetic stimulation depending on the state of contraction or relaxation of the organ at the time of stimulation. The parasympathetic also augments intestinal secretion.



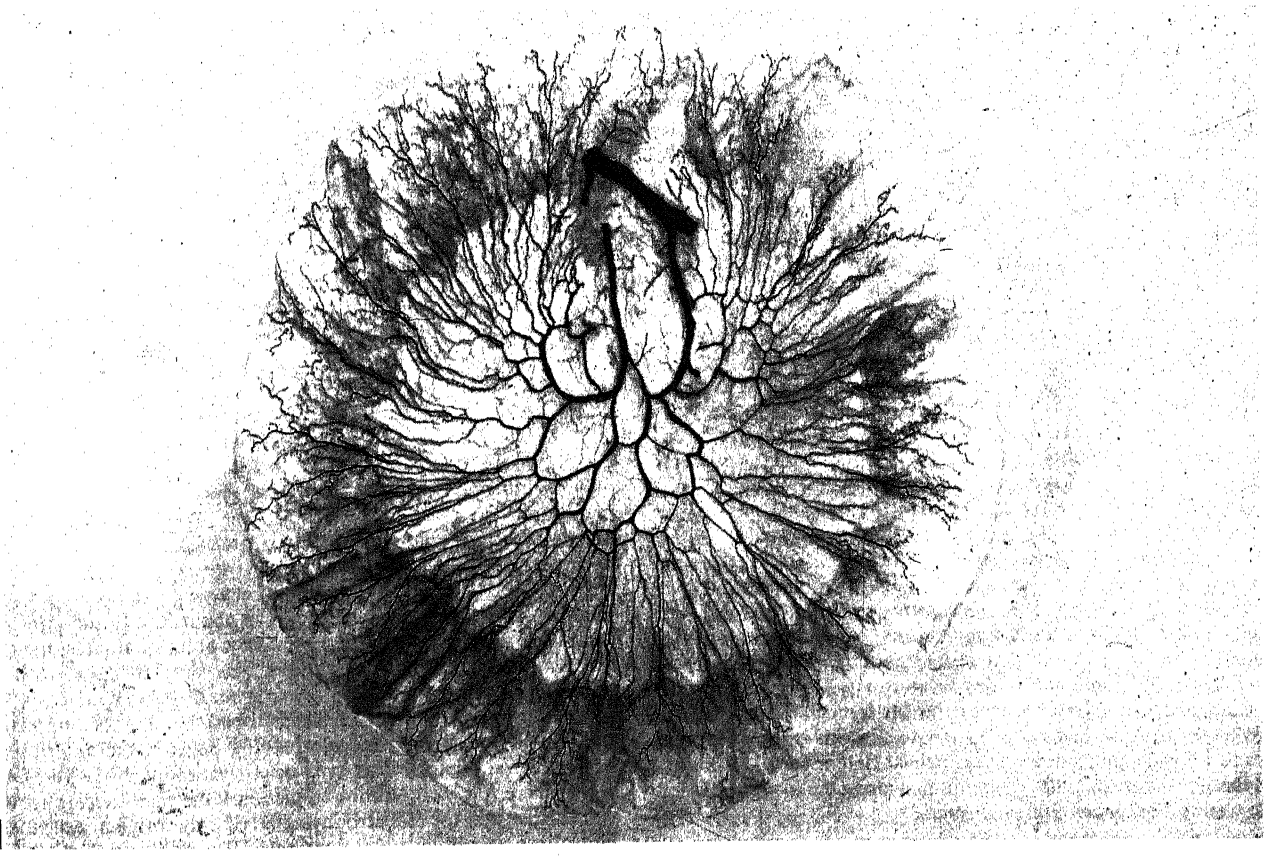
12.111A, B Aggregated lymphatic follicles in the proximal (A) and distal (B) parts of the ileum.



12.111c Electron micrograph of a section through a lymphatic vessel from the small intestine (rat) showing numerous fat droplets (chylomicrons) within the vessel lumen; also visible is a bundle of enteric plexus axons (lower right). (Provided by G Gabella, Department of Anatomy and Embryology, University College London.)

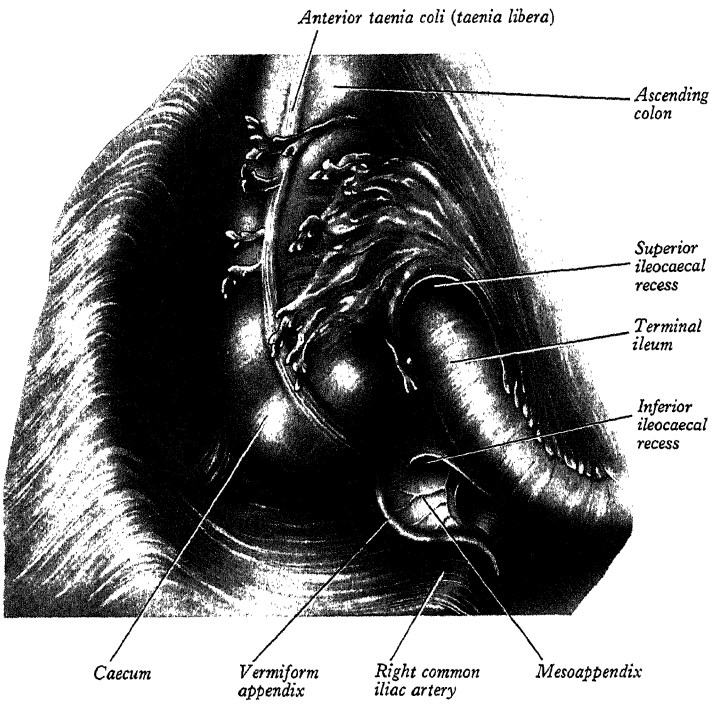


A

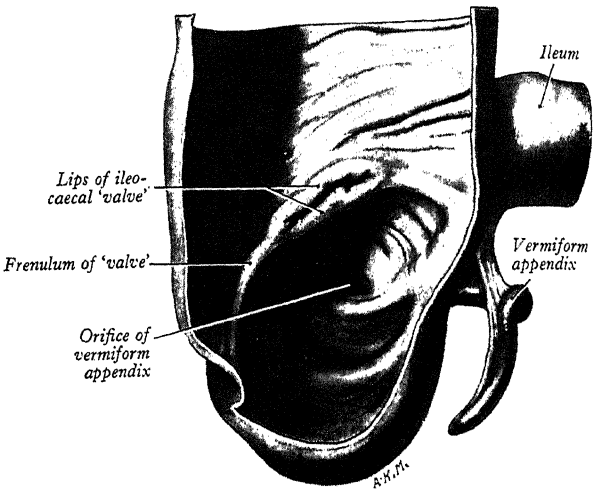


B

12.112 Specimens of the jejunum (A) and ileum (B) from a subject in whom the superior mesenteric artery was injected with a red coloured mass of gelatin before fixation. Subsequently the specimens were dehydrated and then cleared in benzene followed by methyl salicylate. The largest vessels present are the jejunal and ileal branches of the superior mesenteric artery and these are succeeded by anastomotic arterial arcades, which are relatively few in number (1–3) in the jejunum, becoming more numerous (5–6) in the ileum. From the arcades, straight arteries pass towards the gut wall; frequently, successive straight arteries are distributed to opposite sides of the gut. Note the denser vascularity of the jejunal wall. (Specimens prepared by Michael C E Hutchinson and photographed by K Fitzpatrick, Department of Anatomy, Guy's Hospital Medical School, London.)



12.113 The terminal ileum, caecum and vermiform appendix: anterior aspect.



12.114 The interior of the caecum and commencement of the ascending colon, showing the ileocaecal 'valve'. See text for discussion.

LARGE INTESTINE (12.113–127)

The large intestine, extending from the distal end of the ileum to the anus, is about 1.5 m long; its calibre is greatest near the caecum and gradually diminishes to the rectum, where it enlarges just above the anal canal. Its function is chiefly absorption of fluid and solutes, and it differs in structure, size and arrangement from the small intestine in the following ways:

- it has a greater calibre
- it is for the most part more fixed in position
- its longitudinal muscle, though a *complete* layer, is concentrated into three longitudinal *taeniae coli*
- the colonic wall is puckered into *sacculations* (*haustrations*) by the taeniae (so it is said) but sacculation is probably not thus fully explained (p. 1784; see also Hamilton 1946; Pace 1968).

Small adipose projections, *appendices epiploicae*, are scattered over the free surface of the whole colon, but are absent from the caecum, vermiform appendix and rectum.

The large intestine (**12**.117, 118) curves around the coils of the small intestine, commencing in the right iliac region as a dilated *caecum* (*intestinum crassum caecum*). (The term *caecum*, like rectum, duodenum, etc. is an adjective, used by linguistic abbreviation as a noun.) The caecum leads to the *vermiform appendix* and *colon*, the latter ascending in the right lumbar and hypochondriac regions to the inferior aspect of the liver; here it bends (*right colic flexure*) to the left and, with an antero-inferior convexity, loops across the abdomen as the *transverse colon* to the left hypochondriac region, where it curves again (*left colic flexure*) to descend through the left lumbar and iliac regions to the lesser pelvis. Here it forms a sinuous loop, the *sigmoid colon* (**12**.119), continuing along the lower posterior pelvic wall as the *rectum* and *anal canal*.

CAECUM (12.113, 114)

The caecum (**12**.113, 114) lies in the right iliac fossa; its surface projection occupies the triangular area between the right lateral and transtubercular planes and the inguinal ligament. It is a large cul-de-sac continuous with the ascending colon at the level of the ileal opening on the medial side and below this with the vermiform appendix. Its average axial length is about 6 cm and its breadth about 7.5 cm. It is superior to the lateral half of the inguinal ligament, resting posteriorly on the right iliacus (with the lateral cutaneous nerve of the thigh interposed) and psoas major, separated from both by covering fasciae and peritoneum. Posterior to it is the *retrocaecal recess* (p. 1744), frequently containing the vermiform appendix. Anteriorly, it usually contacts the anterior abdominal wall, but the greater omentum and, when it is empty, some coils of the small intestine may intervene. Usually it is entirely covered by peritoneum, but sometimes incompletely, when the upper part of the posterior surface is sessile and connected to the iliac fascia by loose connective tissue. Commonly, however, the caecum is mobile, and may even herniate through the right inguinal canal. It can also usually be delivered through an appropriate incision in the anterior abdominal wall at appendicectomy.

Caecal variations

The caecum has been classified into four types (Treves 1885). In early fetal life it is short, conical and broad at the base, with an apex turned superomedially towards the ileocaecal junction. As the fetus grows, the caecum increases more in length than breadth, to form a longer tube with a narrower base but retaining the same inclination. Distal growth later ceases, but the proximal part continues to grow in breadth, so that at birth a narrow vermiform appendix extends from the apex of a conical caecum. This *infantile form* persists throughout life in about 2%, regarded by Treves as the *first type*; the three taeniae coli (p. 1784) start from the appendix and are equidistant from each other. In the *second type*, the conical caecum becomes quadrate by outgrowth of a saccule on each side of the anterior taenia; these saccules are of equal size and the appendix arises from the depression between them instead of from the apex of a cone. This type occurs in about 3%. In the *third type* (normal in humans) the two saccules grow at unequal rates, the right more rapidly, forming a new 'apex'; the original apex, with the appendix attached, is pushed towards the ileocaecal junction; the taeniae still start from the appendicular base but are not equidistant, the growth of the right saccule pushing between the anterior and posterolateral taeniae. This type occurs in about 90%. The *fourth type* is merely an exaggeration of the third, the right saccule growing still further and the left atrophying so that the original caecal apex and appendix are near the ileocaecal junction, the anterior taenia also turning medially to it. This type occurs in about 4%. In a more recent study (Pavlov & Pétrov 1968) of 82 males and 44 females (adolescent and adult), the third type was designated *ampullary*, accounting for 78%. An *infundibular* type, approximating to the infantile conical category, occurred in 13%; 9% were intermediate. The caecum was mobile 20% more often in females. (For further analyses consult Balthazar & Gade 1976.)

ILEOCAECAL VALVE

The ileum opens into the posteromedial aspect of the large intestine, at the junction of the caecum and colon (**12**.114). A surface marking of this structure is the intersection of the right lateral and transtubercular planes; about 2 cm below this the vermiform appendix opens into the caecum. The ileocaecal orifice has a so-called 'valve', consisting of two flaps projecting into the lumen of the large intestine. In the distended, fixed caecum the flaps are semilunar. The upper, approximately horizontal, is attached to the junction of the ileum and colon, the lower, longer and more concave, to the junction of the ileum and caecum. At their ends the flaps coalesce, continuing as narrow membranous ridges, the *frenula* of the valve. The anterior or left end of the aperture is rounded, the right or posterior is narrow and pointed. In the natural state the valvular lips project as thick folds into the caecal lumen, the orifice appearing like a slit or oval. Circular and longitudinal muscle layers of the terminal ileum continue into the valve to form a sphincter. However, direct observation of the living ileocaecal 'valve' does not corroborate this description (Rosenberg & DiDio 1969); in nine cases, studied by caecostomy, the ileal projection was papillary in shape. Radiological evidence also contradicts the concept of an effective ileocaecal valve at this junction.

Accumulations of circular fibres, sometimes described as sphincters, have been observed at various levels in all parts of the colon (DiDio & Anderson 1968; Rosenberg & DiDio 1969). The functional reality of most of these remains doubtful. Such sphincteric mechanisms must, of course, be balanced by antagonistic, dilatatory actions.

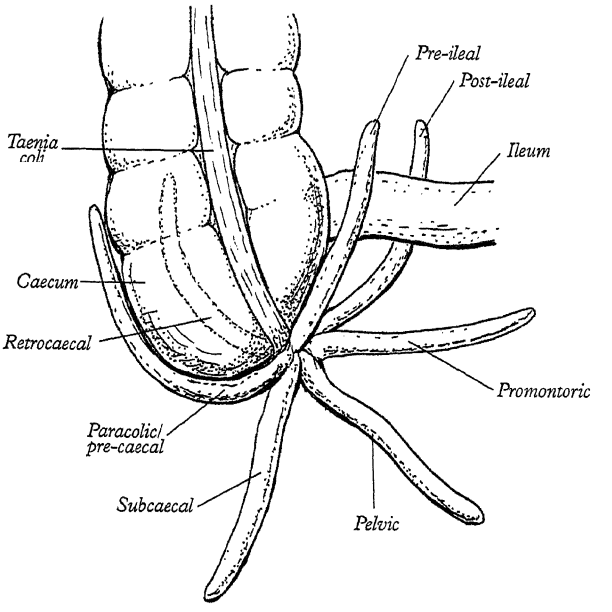
The margin of the ileocaecal valve is a reduplication of the intestinal mucosa and *circular* muscle; longitudinal muscle fibres are partly reduplicated as they enter the valve (Jit & Singh 1956), but the more superficial fibres and the peritoneum continue uninterruptedly from the small to the large intestine. The ileal valvular surfaces are covered with villi and have the structure of the mucosa of the small intestine; their caecal aspects display no villi but numerous orifices of tubular glands peculiar to the colonic mucosa. It is usually said that the valve not only prevents reflux from the caecum to the ileum but is probably also a sphincter regulating the passage of ileal contents into the caecum; the valve is kept in tonic contraction by sympathetic innervation. Entry of food into the stomach initiates contraction of the small intestine, expelling ileal contents into the large intestine (the gastro-ileal reflex).

VERMIFORM APPENDIX

The vermiform appendix (**12**.113–116) is a narrow, vermian (worm-shaped) tube, arising from the posteromedial caecal wall, 2 cm or less below the end of the ileum. It may occupy one of several positions (**12**.115):

- behind the caecum and lower ascending colon (*retrocaecal* and *retrocolic*);
- dependent over the pelvic brim (*pelvic* or *descending*), in females in close relation to the right uterine tube and ovary;
- lying below the caecum (*subcaecal*);
- in front of the terminal ileum when it may be in contact with the anterior abdominal wall;
- behind the terminal ileum.

In 10,000 subjects (Wakeley 1933) the vermiform appendix was retrocaecal and retrocolic (65.28%), pelvic (31.01%), subcaecal (2.26%), pre-ileal (1.0%) and postileal (0.4%). Subsequent literature, anatomical and surgical, shows much contradiction of this classic study. Buschard and Kjaeldgaard (1973), reporting a short series (234 autopsies), compared the results of several studies dating from 1885–1973, Wakeley's remaining by far the largest. They classified all positions as either *anterior* (pelvic and ileocaecal) or *posterior* (retrocaecal and subcaecal). All but three of 11 series quoted found anterior positions more frequent. Like Wakeley they observed posterior positions more commonly in their own Danish series; in German autopsies the finding was reversed. Collins (1932), in the second largest series (4680), returned percentages the reverse of Wakeley's, the ratio of anterior to posterior being 78.5% to 21.5% (Collins) and 32.4% to 67.6% (Wakeley). In view of these disagreements, such figures are of dubious value. Perhaps observers have used differing criteria or possibly there are demographic variations. For the present, however, such percentages remain unreliable.

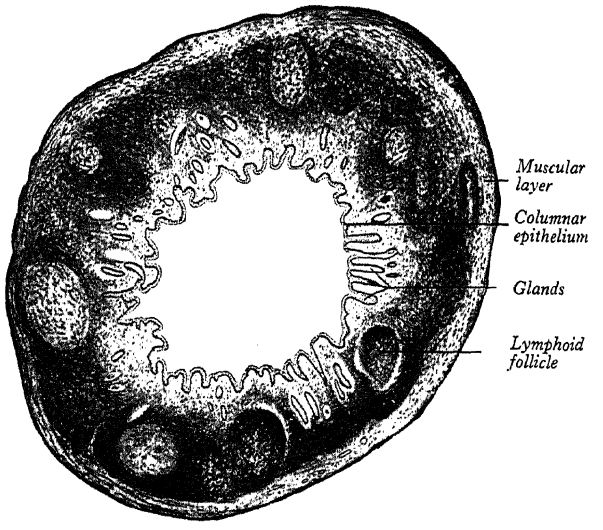


12.115 Diagram illustrating the major positions of the appendix encountered at surgery or post-mortem.

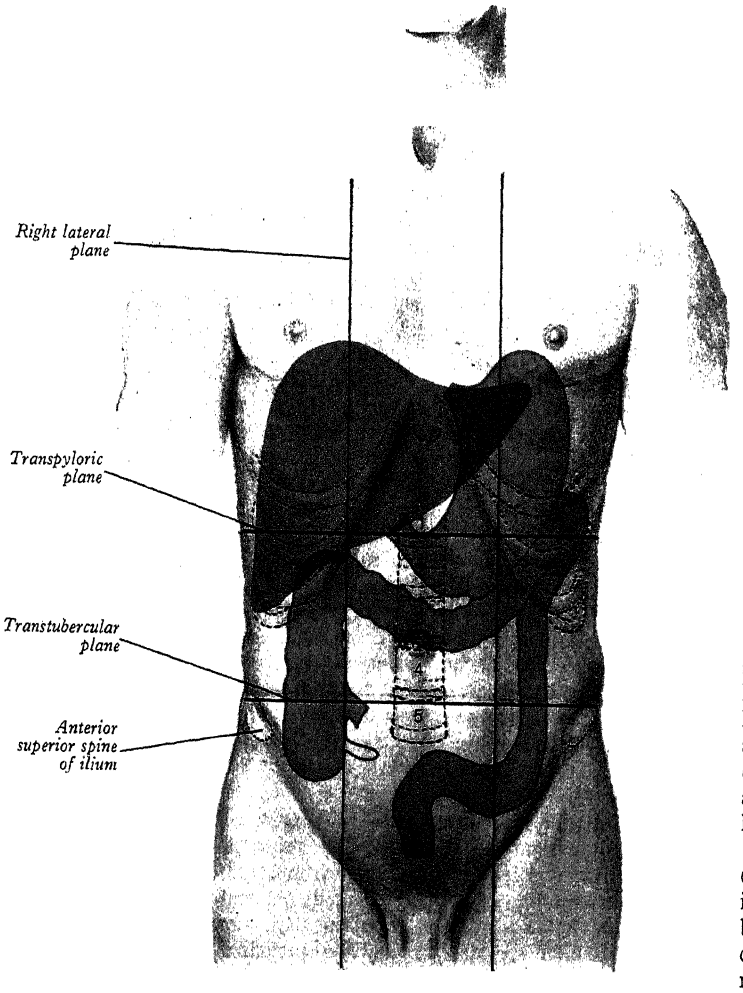
The usual *surface marking* for the appendicular base is the junction of the lateral and middle thirds of the line joining the right anterior superior iliac spine to the umbilicus (*McBurney's point*); but this is merely a useful surgical approximation, with considerable variation. The three taeniae coli on the ascending colon and caecum converge on the base of the appendix, merging into its longitudinal muscle. The anterior caecal taenia is usually distinct and traceable to the appendix, affording a guide to it. The appendix varies from 2–20 cm in length, the average being about 9 cm. It is longer in children and may atrophy or diminish after mid-adult life. It is connected by a short *mesoappendix* to the lower part of the ileal mesentery. This fold is usually triangular, extending almost to the appendicular tip along the whole tube.

The main *appendicular artery*, a branch from the lower division of the ileocolic (p. 1554), runs behind the terminal ileum to enter the mesoappendix a short distance from the appendicular base. Here it gives off a recurrent branch which anastomoses at the base of the appendix with a branch of the posterior caecal artery, the anastomosis sometimes being large. The main appendicular artery approaches the tip of the organ, at first near to and then in the edge of the mesoappendix. The terminal part of the artery, however, lies on the wall of the appendix and may be thrombosed in appendicitis, resulting in distal gangrene or necrosis. The arterial supply of the appendix may vary considerably. Accessory arteries are common; in 80% of subjects there are two or more arteries of supply (Solanke 1968).

The canal of the appendix is small and opens into the caecum by an orifice lying below and a little behind the ileocaecal opening. The orifice is sometimes guarded by a semilunar mucosal fold forming a valve. The lumen may be partially or wholly obliterated in the later decades of life. In view of its rich vascularity and histological differentiation, the appendix is probably a specialized rather than a degenerate or vestigial structure. The caecum and appendix in man and anthropoid apes is considered to be less primitive than in monkeys. A comparative study of the primate vermiform appendix has been made by Scott (1980).



12.116 Transverse section of human vermiform appendix. Magnification × 20.



12.117 Surface projection of the stomach, liver and colon. The outlines of the lumbar vertebral bodies and intervertebral discs, lower ribs, xiphoid process and parts of the iliac crests are indicated.

Microstructure of the appendix

The layers of the appendix wall are essentially as in the rest of the large intestine. The *serosa* is a complete investment, except along the mesenteric attachment; there is a subserous layer of connective tissue. The *longitudinal muscular fibres* form a complete, uniformly thick layer, except over a few small areas where both muscular layers are deficient, leaving the serosa and submucosa in contact. At the base the longitudinal muscle thickens to form rudimentary taeniae continuous with those of the caecum and colon. The *circular muscular fibres* form a thicker layer separated from the longitudinal by connective tissue. The *submucosa* is well developed, containing many lymphoid masses which cause the mucosa to bulge into the lumen, narrowing it irregularly. The *mucosa* is covered by columnar epitheliocytes and attenuated antigen-transporting 'M' cells (Owen & Nemanic 1978). Glands (crypts similar to those of the colon) are few and penetrate deeply into the lymphoid tissue (**12.116**), which in the normal human appendix is situated primarily in the lamina propria and extends into the submucosa; follicular and parafollicular zones containing B- and T-lymphocytes (p. 1417) can be distinguished; clustered lymphocytes also appear between the epithelial cells, where some may possibly differentiate into plasma cells (Gorgollón 1978). Lymphoid tissue in the lamina propria contains many plasma cells, with lymphocytes, eosinophils and other leucocytes, mast cells and macrophages embedded in a fibrocellular reticulum. The submucosal follicles (germinal centres) are organized like those of other examples of gut-associated lymphoid tissue (p. 1417; see also Kaiserling et al 1974). The *lymphoid masses* are a local defence against infection; it has also been suggested that they may be a homologue of the avian *bursa of Fabricius* concerned in the acquisition of immunological competence by certain lymphocytes. However, experimental evidence argues against this function (p. 1417). In many mammals, particularly herbivores, the caecum and appendix are large and constitute a highly important site of digestion of cellulose by symbiotic bacteria.

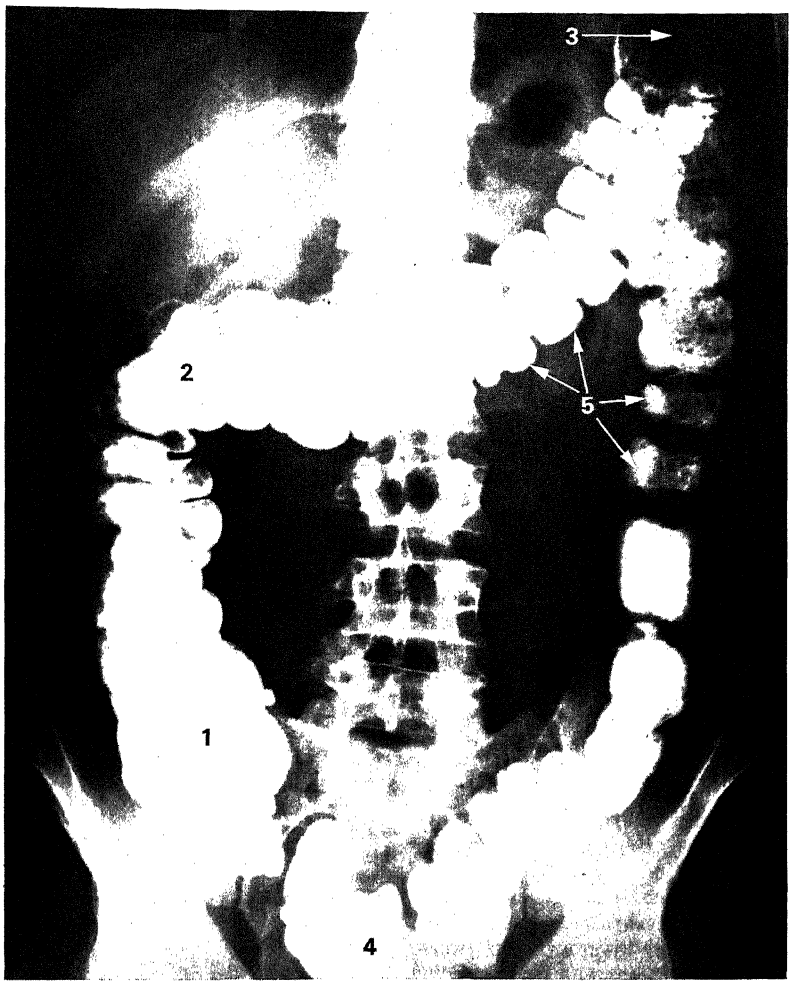
COLON (**12.117, 118, 123**)

The colon is conveniently considered in four parts: ascending, transverse, descending and sigmoid.

Ascending colon. About 15 cm long and narrower than the caecum, it ascends to the inferior surface of the right lobe of the liver, on which it makes a shallow depression; here it turns abruptly forwards and to the left, at the *right colic flexure* (**12.95**). In surface projection it ascends lateral to the right lateral plane (**12.117**) from the transtubercular to midway between the subcostal and transpyloric planes. It is covered by peritoneum except where its posterior surface is connected by loose connective tissue to the iliac fascia, and to the iliolumbar ligament, quadratus lumborum, aponeurosis of transversus abdominis and the perirenal fascia on the front of the inferolateral area of the right kidney. Crossing behnd it are the lateral femoral cutaneous nerve, usually the fourth lumbar artery, and sometimes the ilio-inguinal and iliohypogastric nerves. Sometimes it possesses a distinct but narrow mesocolon. In a series of 100 subjects, 52% had neither an ascending nor descending mesocolon, 14% had both, 12% an ascending and 22% a descending mesocolon (Treves 1885). Anteriorly it is in contact with the coils of the ileum, the greater omentum and the anterior abdominal wall.

Right colic flexure. This is found at the junction of the ascending and transverse colon; the latter turns down, forwards and to the left. Posterior is the inferolateral part of the anterior surface of the right kidney; above and anterolaterally is the right lobe of the liver; anteromedially are the descending part of the duodenum and fundus of the gallbladder. Its posterior aspect is not covered by peritoneum and is in direct contact with renal fascia. It is not so acute as the left colic flexure.

Transverse colon (**12.88, 89, 117, 118**). About 50 cm long, it extends from the right colic flexure in the right lumbar region, across into the left hypochondriac region, here curving sharply down and backwards below the spleen as the *left colic flexure*. The transverse colon describes an arch, its concavity usually directed back and up; near its splenic end an abrupt U-shaped curve may descend lower than the main arch. Its surface projection (**12.117**) extends from a point situated just lateral to the right lateral plane, and midway between the subcostal and transpyloric planes, to the umbilicus and



12.118 A radiograph of the abdomen after the administration of a barium enema which has filled the whole of the large intestine as far as the caecum and ileocaecal valve. (1) the caecum; (2) the right or hepatic flexure of the colon, which is much inferior to (3) the left or splenic flexure of the colon; (4) the sigmoid colon; (5) the sacculations, or haustrations, which are clearly visible throughout most of the colon.

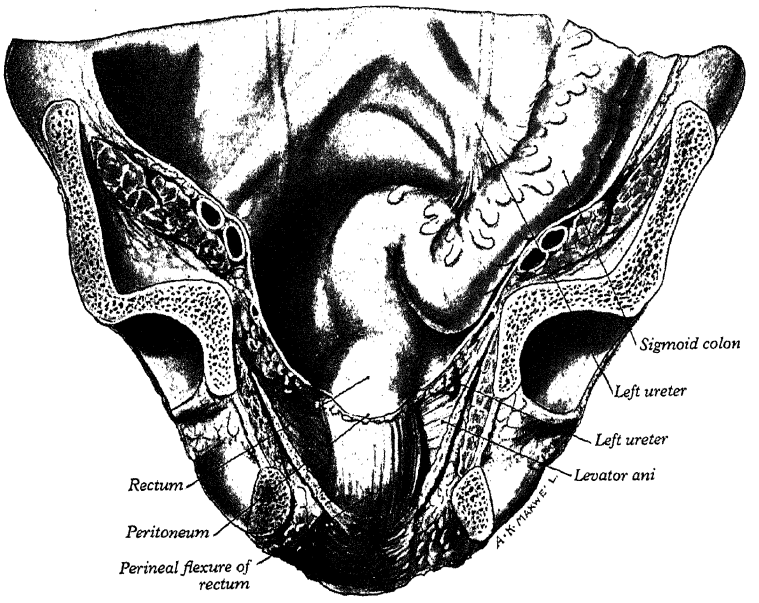
then up and left to a point just superolateral to the intersection of the left lateral and transpyloric planes. A precise projection is difficult to define, varying much even in the same individual. Commonly it is in the lower umbilical or upper hypogastric region. It frequently descends in a V-shaped manner, the apex being well below the level of the iliac crests (p. 1734). In a radiological assessment in the upright position, its lowest level in 1000 young adults was found to vary much, even reaching the true pelvis; levels varied as much as 17 cm in the same individual between upright and recumbent positions (Moody 1927).

The posterior surface at its right end is devoid of peritoneum and is attached by loose connective tissue to the front of the descending part of the duodenum and the head of the pancreas; but from the latter to the left colic flexure it is almost completely invested by peritoneum, connecting it to the anterior border of the body of the pancreas by the *transverse mesocolon*. Above the transverse colon are the liver and gallbladder, the greater gastric curvature and the lateral end of the spleen; below is the small intestine, in front are the posterior layers of the greater omentum and behind are the descending part of the duodenum, the head of the pancreas, the upper end of the mesentery, the duodenojejunal flexure and coils of the jejunum and ileum.

Left colic flexure (12.96). This is the junction of the transverse colon and descending colon in the left hypochondriac region; it is related to the lower part of the spleen and pancreatic tail above and medially with the front of the left kidney. It is so acute that the end of the transverse colon usually overlaps the front of the descending colon. The left flexure is above and on a more posterior plane than the right flexure and is attached to the diaphragm level with the tenth and eleventh ribs by the *phrenicocolic ligament*, which lies below the anterolateral pole of the spleen (p. 1743).

Descending colon (12.96). About 25 cm long, it descends through the left hypochondriac and lumbar regions, at first following the lower part of the lateral border of the left kidney and then descending in the angle between the psoas major and quadratus lumborum to the iliac crest; it then curves downwards and medially in front of the iliacus and psoas major to end in the sigmoid colon at the inlet of the lesser pelvis. (It is sometimes described as ending at the iliac crest, the part between this and the pelvic inlet being named the *iliac colon*.) In surface projection (12.117) it descends just lateral to the left lateral plane, from a little above and left of the intersection of the transpyloric and left lateral planes as far as the inguinal ligament. Peritoneum covers all but its posterior surface, which is connected by loose connective tissue to fascia over the inferolateral region of the left kidney, the aponeurosis of transversus abdominis, the quadratus lumborum, iliacus and psoas major (12.96). Crossing behind it are the following left structures: subcostal vessels and nerve, iliohypogastric and ilio-inguinal nerves, fourth lumbar artery (usually), the lateral femoral cutaneous, femoral and genitofemoral nerves, the testicular (or ovarian) vessels and the external iliac artery. The descending colon is smaller in calibre, more deeply placed, and more frequently covered behind by peritoneum than the ascending colon (p. 1776). Anteriorly are the coils of the jejunum, except for its lower part which is palpable when the abdominal muscles are relaxed.

Sigmoid colon (pelvic colon) (12.119). It begins at the pelvic inlet, continuing in the descending part; it forms a variable loop of about 40 cm and is normally in the lesser pelvis. The loop first descends in contact with the left pelvic wall, then crosses the pelvic



12.119 Oblique coronal section through the pelvis to expose the anterior aspect of the rectum.

cavity between the rectum and bladder in males, and rectum and uterus in females, and may reach the right pelvic wall; finally it turns back to the midline level with the third piece of the sacrum, where it bends downwards and ends in the rectum. It is closely surrounded by peritoneum, forming a mesentery, the *sigmoid mesocolon* (p. 1743), which diminishes in length from the centre towards its ends, where it disappears; the loop is fixed at its junctions with the descending colon and rectum but quite mobile between them. Its relations are therefore variable. **Laterally** are: the left external iliac vessels, the obturator nerve, ovary or ductus deferens and the lateral pelvic wall; **posteriorly** the left internal iliac vessels, ureter, piriformis and sacral plexus; **inferiorly** the bladder in males or uterus and bladder in females; **superiorly** and to the **right** it is in contact with terminal coils of the ileum.

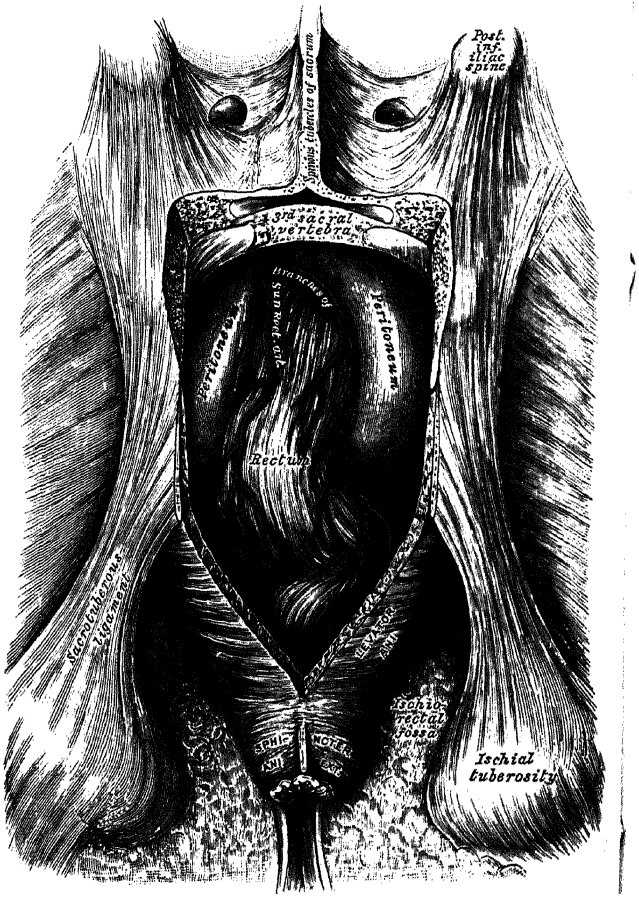
The position and shape of the sigmoid colon vary much, depending on:

- its length
- the length and mobility of its mesocolon
- the degree of distension (when distended it rises into the abdominal cavity, sinking again into the lesser pelvis when empty)
- the condition of the rectum, bladder and uterus (when these are distended the sigmoid colon tends to rise and to fall when they are empty).

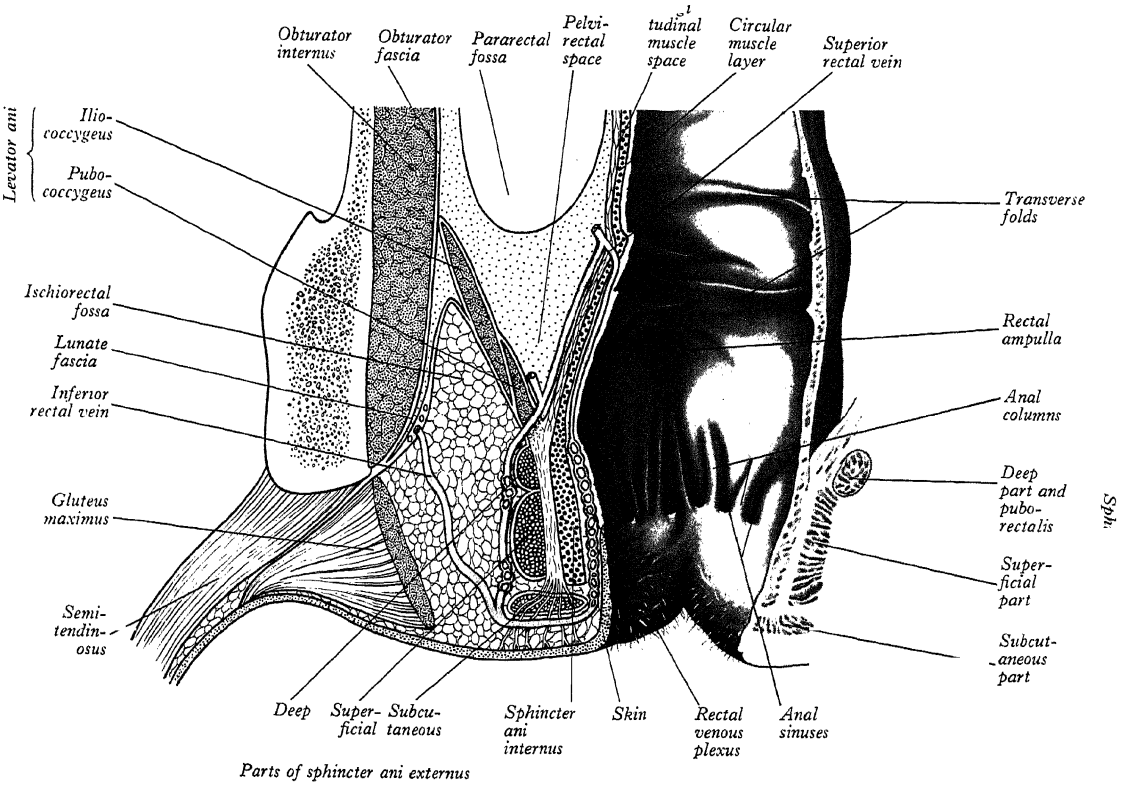
Racial variation has been noted (Lisowski 1969): in some groups, particularly Ethiopians, the incidence of a suprapelvic loop, perhaps conducive to volvulus, is particularly high.

RECTUM

The rectum (**12.119, 120, 121**) is continuous with the sigmoid colon at the level of the third sacral vertebra, the junction being at the lower end of the sigmoid mesocolon. The rectum descends along the sacrococcygeal concavity, with an anteroposterior curve, the *sacral flexure* of the rectum. It thus curves down and back, then downwards, and finally down and forwards to join the anal canal by passing through the pelvic diaphragm (p. 830). The *anorectal junction* is 2–3 cm in front of and slightly below the tip of the coccyx; from this level (in males opposite the apex of the prostate) the anal canal passes down and backwards from the lower end of the rectum, this backward bend of the gut being termed the *perineal flexure* of the rectum. The rectum also deviates in three lateral curves: the upper is convex to the right, the middle (the most prominent) bulges to the



12.120 Posterior aspect of the rectum exposed by removal of the lower part of the sacrum and coccyx. Note the superior rectal artery (red) and peritoneum of the pararectal fossae (blue).



12.121 Diagram of a coronal section of the rectum and anal canal and the adjacent structures (adapted from Rauber-Kopsch, *Lehrbuch und Atlas der Anatomie des Menschen*, 1919). The internal pudendal vessels, the dorsal nerve of the penis and the perineal nerve are shown transected in the lateral wall of the ischiorectal fossa, where they are traversing the 'lunate fascia' (pudendal canal).

left and the lower is convex to the right. Both ends of the rectum are in the median plane.

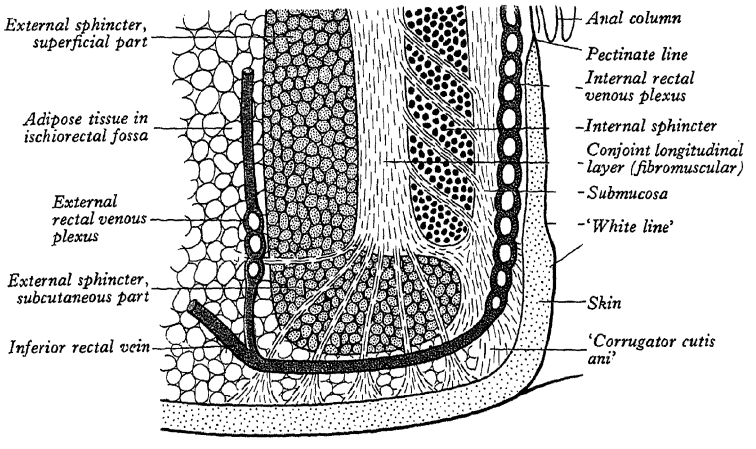
The rectum is about 12 cm long, with the same diameter as the sigmoid colon above (about 4 cm in the empty state), but its lower part is dilated as the *rectal ampulla*. The rectum differs from the sigmoid colon in having no sacculations, appendices epiploicae or mesentery; the taeniae blend about 5 cm above the rectosigmoid junction, forming two wide muscular bands which descend, anterior and posterior, in the rectal wall. The peritoneum is related only to the upper two-thirds, covering its front and sides above, and lower down only its front, from which it is reflected on to the bladder in males, forming the rectovesical pouch, and on to the posterior vaginal wall in females, forming the recto-uterine pouch. The level of this reflexion is higher in males, the rectovesical pouch being about 7.5 cm (about the length of the index finger) from the anus; in females the recto-uterine pouch is about 5.5 cm from the anus. In the male fetus, peritoneum extends on to the front of the rectum as far as the lower limit of the prostate (p. 1859). On the sigmoid colon, peritoneum is firmly attached to the muscle layer by fibrous connective tissue but as it descends on to the rectum it is more loosely attached by fatty connective tissue, allowing for considerable expansion.

In the empty rectum, the mucosa in its lower part presents a number of longitudinal folds which become effaced during distension. There are also permanent semilunar *transverse* or *horizontal folds*, most marked in rectal distension. Two forms of horizontal fold have been recognized (Jit 1961); one consists of the mucosa, a circular muscle layer and part of the longitudinal muscle, and an indentation on the rectal exterior; the other is devoid of longitudinal muscle and has no external marking. Their number is variable but there are commonly three folds. An upper one, near the beginning of the rectum, may be either on the left or right; occasionally it encircles the gut, constricting its lumen. The middle fold is largest and most constant; it lies immediately above the ampulla, projecting from the anterior and right wall just below the level of the anterior peritoneal reflexion; the circular muscle is more marked in this fold than in the others. The lowest fold, inconstant and on the left, is about 2.5 cm below the middle fold. Sometimes a fourth occurs on the left about 2.5 cm above the middle fold.

It has been suggested (Paterson 1912) that the rectum consists of two functional parts, above and below the middle fold, the upper containing faeces and being free to distend into the peritoneal cavity, the lower more confined, enclosed in a tube of condensed extraperitoneal tissue and (except during defaecation) normally empty; in chronic constipation or after death it may contain faeces. (Note that the rectum above the middle fold is considered to develop from the hindgut and the part below, with the upper anal canal, to originate from the cloaca or postallantoic gut.) Others (O'Beirne 1833; Hurst 1919) have considered the sigmoid colon a faecal reservoir, the rectum being normally empty and the entry of faeces into it exciting defaecation. Experimental distension of the rectum and anal canal results in the desire to defaecate and causes the relaxation of the anal sphincters (Denny-Brown & Robertson 1935).

Relations of the rectum

Posterior to the rectum in the median plane are: the lower three sacral vertebrae, coccyx, median sacral vessels, ganglion impar and branches of the superior rectal vessels; while on each side, particularly on the left, are: the piriformis, the anterior rami of the lower three sacral and coccygeal nerves, sympathetic trunk, lower lateral sacral vessels, the coccygei and the levatores ani. The rectum is attached to the sacrum along the lines of the anterior sacral foramina by fibrous connective tissue enclosing: the sacral nerves and the pelvic splanchnic nerves from the anterior rami of the second to fourth sacral nerves, which join the pelvic plexuses on the rectal wall; rami of the superior rectal vessels, lymphatic vessels, lymph nodes; and loose perirectal fat. **Anterior in males** above the site of the peritoneal reflexion from the rectum are the upper parts of the base of the bladder and of the seminal vesicles, the rectovesical pouch and its contents (terminal coils of the ileum and sigmoid colon); below the reflexion are: the lower parts of the base of the bladder and of the seminal vesicles, deferent ducts, terminal parts of the ureters and



12.122 Part of **12.121** enlarged to show greater detail.

the prostate. **In females**, above the reflexion are: the uterus, upper vagina, recto-uterine pouch and contents (terminal coils of the ileum and sigmoid colon), while below the reflexion is the lower part of the vagina. **Laterally**, the upper part of the rectum is related to the pararectal fossa and contents (sigmoid colon or lower ileum), while below the peritoneal reflexion laterally are the pelvic sympathetic plexuses, coccygei and levatores ani and branches of the superior rectal vessels.

ANAL CANAL (12.121–123)

The anal canal (Milligan et al 1937; Gabriel 1945; Wilde 1949; Goligher et al 1955; Fowler 1957) begins where the rectal ampulla suddenly narrows, passing down and backwards to the anus (**12.121**, 122). It is about 4 cm long in adults, its anterior wall being slightly shorter than its posterior. When empty its lumen is a sagittal or triradiate longitudinal slit. **Posterior** is a mass of fibromuscular tissue, the *anococcygeal ligament*, separating it from the tip of the coccyx; **anteriorly** it is separated by the *perineal body* (p. 833) from the membranous urethra and penile bulb or from the lower vagina; **laterally** are the ischiorectal fossae. Over its whole length it is surrounded by sphincters which normally keep it closed.

Lining of the anal canal

The lining of the anal canal varies along its course. The mucosa of the lower part of the rectum is pale pink and semitransparent, the branching pattern of the superior rectal vessels being visible through it. The upper half (15 mm) of the anal canal is also lined by mucosa, plum-red in colour due to blood in the subjacent internal rectal venous plexus. The epithelium is variable. In the upper part it is similar to that of the rectum, consisting of simple columnar cells, some secretory and others absorptive, with numerous tubular glands or crypts. In the lower half, this gives way to non-keratinized stratified squamous epithelium of the perianal epidermis (Walls 1958). In this part of the canal are 6–10 vertical folds, the *anal columns*, well marked in children but sometimes less defined in adults (**12.121**). Each column contains a terminal radicle of the superior rectal artery and vein, these radicles being largest in the left-lateral, right-posterior and right-anterior quadrants of the wall of the canal; enlargements of venous radicles in these three sites constitute primary internal haemorrhoids. The lower ends of the columns are linked by small crescentic mucous folds, the *anal valves*, above each of which is a small recess or *anal sinus*. The sinuses, deepest in the posterior wall, may retain faecal matter and become infected, leading to abscess formation in the anal canal wall; anal valves may be torn by hard faeces, producing an anal fissure (p. 1782). Anal valves are situated along the *pectinate line*, opposite the middle of the sphincter ani internus and commonly considered to be the site of the anal membrane in early fetal life, thus representing the junction of the endodermal (cloacal) and ectodermal (proctodeal) parts of the canal. Small epithelial anal papillae may occur on the edges of the anal valves, perhaps remnants of the anal membrane. However, the junction of ectodermal and endodermal parts may be at the lower border of the pecten (Johnson 1914).

The anal canal extends about 15 mm below the anal valves, as the *transitional zone* or *pecten*, whose epithelium is non-keratinized, stratified squamous and intermediate in thickness between that of the mucosa of the upper part of the canal and the epidermis in its lowest part; only the latter contains sweat glands. The transitional zone overlies part of the internal rectal venous plexus and is shiny and bluish. Its submucosa contains dense connective tissue, contrasting with the lax connective tissue in the upper half of the anal canal and suggesting the firm support and anchorage of the pectineal lining to the surrounding anal muscle. The transitional zone ends below at a narrow sinuous zone, the *'white line'* (of Hilton). In the living this 'line' is bluish pink and rarely visible (Ewing 1954), its only interest being that it is at a level between the subcutaneous part of the external sphincter and the lower border of the internal sphincter; digital examination in the living reveals an *anal intersphincteric groove* at this site. Below the white line, the final 8 mm or so of the anal canal is lined by true skin, dull white or brown in colour and containing sweat and sebaceous glands. There is much variation in the epithelial zones described above and frequently the various types interpenetrate, the zones being poorly defined.

Near the anal sinuses, *anal glands* (Fowler 1957; McColl 1967) extend upwards or downwards into the submucosa, occasionally penetrating deeply into the internal sphincter. Each consists of one to six spiral or straight tubules, sometimes branched, and lined by two or three layers of mucous secretory cells. The duct of each gland, lined by stratified columnar epithelium, opens into a small depression, an *anal crypt*. The glands are surrounded by lymphocytes in a form similar to lymphatic follicles and the submucosal smooth muscle is thick in their vicinity. Occasionally the termination of a duct is not canalized and secretions may then form a cyst. The glands are sometimes infected, producing an abscess or fistula. They vary widely in number and depth of penetration, even extending into the submucosa above the anorectal junction. For details of comparative anatomy and pathology see McColl 1967. In this study, 50 normal anal canals were examined; half had anal glands passing right through the internal sphincter; the average number of such extensions was four but the range extended up to 16. McColl considered that these human glands were not homologous with the *anal scent glands* of some other mammals.

ANAL MUSCULATURE (12.121, 122)

The anal walls are surrounded by a complex tube of sphincters which tightly occlude the anal canal except during defaecation. The muscular components are divisible into the internal and external anal sphincters (*sphincter ani internus* and *sphincter ani externus*) and the *puborectalis* muscle which is part of levator ani (p. 831). There are also longitudinal muscle components forming the *conjoint longitudinal coat*.

Sphincter ani internus (internal sphincter)

The sphincter ani internus is a thickened (5–8 mm wall) tube of circular smooth muscle representing a thickening of the rectal muscularis externa. It encloses the upper three-quarters (30 mm) of the anal canal, extending from the anorectal junction down to the white line which marks its lower border.

Sphincter ani externus (external sphincter)

The sphincter ani externus is a tube of skeletal muscle situated externally to the muscularis externa and surrounding the whole anal canal (**12.121**). It is usually described as consisting of three parts. These are, from superior to inferior, the *deep*, *superficial* and *subcutaneous* parts. However, a clear threefold separation has also been denied (Goligher et al 1955). In females according to Oh and Kark (1972) and Wendell-Smith and Wilson (1991) the muscle forms a single band anteriorly. In the present account we will follow the classical description.

Deep part. This is a thick annular band around the upper part of the internal sphincter; its deeper fibres blend inseparably with the puborectalis muscle (p. 831); anterior to the anal canal many of its fibres decussate into the superficial transverse perineal muscles,

especially in females. Some posterior fibres are usually attached to the anococcygeal raphe.

Superficial part. This lies above the subcutaneous part and surrounds the lower part of the internal sphincter. Viewed from above it is elliptical, being attached anteriorly to the perineal body, and posteriorly to the coccyx (the posterior surface of its last segment) via the median anococcygeal raphe, and hence being the only part of the external sphincter attached to bone.

Subcutaneous part. This is a flat band, about 15 mm broad, circumscribing the lower anal canal; it lies horizontally below the lower border of the internal sphincter and superficial part of the external sphincter; it is deep to the skin at the anal orifice and inferior to the white line. Anteriorly a few fibres join the perineal body (or the superficial transverse perineal muscles); posteriorly some fibres are usually attached to the anococcygeal ligament.

Muscle fibre types. Histochemically the external sphincter is composed mainly of Type I (slow twitch) skeletal muscle fibres, which are well suited to prolonged contraction (p. 739), although there are more fast twitch (type II) fibres in children (Lierse et al 1993).

Puborectalis

The puborectalis, the most medial portion of levator ani (histologically skeletal muscle), a band of muscle which loops posteriorly around the anorectal junction, slinging it forwards towards the pubis; some of its fibres mingle with those of the deep part of the external sphincter while others join the longitudinal (smooth) muscle of the anal canal to form the conjoint longitudinal coat (see below). Some of its fibres also pass in front of the anorectal junction, although these are relatively few so that the muscular ring around the anorectal junction is thinner at the front than posteriorly.

The conjoint longitudinal coat

The conjoint longitudinal coat is a fibromuscular layer surrounding the anal canal and situated between the internal and external sphincters. It is formed at the anorectal junction by the fusion of the puborectal fibres of levator ani with the longitudinal layer of the rectal muscularis externa (**12**.122). Distally, this layer is increasingly fibro-elastic; at the white line it breaks up into 9–12 circumferential septa which radiate outwards mainly through the subcutaneous part of the external sphincter to become attached to the dermis of the circumanal skin. These septa are composed largely of elastic fibres; the most peripheral of the septa extend between the subcutaneous and superficial parts of the external sphincter into the ischiorectal fat. The most central (juxta-anal) septum is said to pass between the internal sphincter and the subcutaneous part of the external sphincter to reach the anal lining at the white line as the *anal intermuscular septum*, producing an anal *intersphincteric groove*. Wilde (1949), Goligher et al (1955) and Fowler (1957), however, considered that the longitudinal fibres in this position (compared with those penetrating the subcutaneous part of the external sphincter) were too scanty to warrant a name, maintaining that the groove is due to the muscle masses of the internal sphincter above and the subcutaneous part of the external sphincter below and to the contraction of the latter.

Other fibromuscular structures of the anal canal

In the anal submucosa, inferior to the anal sinuses, is a layer composed of smooth muscle, yellow elastic fibres and collagenous connective tissue, derived mainly from strands of the conjoint longitudinal coat, which descends inwards between the fascicles of the internal sphincter (**12**.121, 122). Some of the strands end by turning outwards around the lower edge of the internal sphincter to rejoin the main longitudinal layer, but most continue obliquely downwards and inwards, then superficial to the subcutaneous part of the external sphincter, inserting into the dermis from the white line to well beyond the anus. These attachments corrugate the region so that the name *corrugator cutis ani* muscle has been attributed to it. However, there is some dispute about whether it is indeed a muscle: Wilde (1949) considered its fibres to be exclusively elastic, but Goligher et al (1955) noted smooth muscle fibres among them. Fowler (1957), finding no muscle fibres here, ascribed puckering of the perianal skin to the combined effects of levator ani and the subcutaneous part of the external sphincter.

The radiating elastic septa end in a network dividing the narrow cleft between the subcutaneous part of the external sphincter and the skin into a compact honeycomb-like arrangement of fibres, which may explain the severe pain produced by pus or blood collecting here, and the localization of a haemorrhage following the rupture of a vein from the external rectal plexus (p. 1309).

A *muscularis mucosae* has also been described in the anal canal immediately above the pectinate line and possibly extending below it (Jit 1974).

Actions of anal muscles in anal closure

Muscle tone in both internal and external sphincters keeps the canal and anus closed except during defaecation, their contraction increasing when the intra-abdominal pressure rises, e.g. in forced expiration, muscular straining, coughing, parturition, etc.

The external sphincter can also be voluntarily contracted to occlude the anus more firmly. It is likely that the external sphincter is more effective at closure than the internal, which appears unable to seal off the anal canal completely (Lestar et al 1992). Puborectalis, forming a sling around the posterior aspect of the deep sphincter, pulls the upper part of the canal forward to form the anorectal angle, thus assisting its closure.

In resting conditions the anal sphincters undergo periodic increased contractions at the rate of about 15 per minute, with some reversal of peristaltic action, presumably helping to prevent leakage, and returning faecal debris to the rectum.

Defaecation

During defaecation a number of co-ordinated actions occur in the muscles of the pelvic floor including the internal and external sphincters, levator ani, and other perineal muscles (Wendell-Smith & Wilson 1991). These have been studied using various imaging techniques including radiography, ultrasonography and magnetic resonance imaging (MRI) (see e.g. Kruyt et al 1991).

Prior to defaecation, faeces move from the colon by peristaltic action into the rectum (from which they are usually excluded except during this process), initiating the desire to defaecate; faeces as far proximally as the splenic flexure may be moved to the rectum in one defaecatory event. When defaecation itself commences, the anorectal (perineal) angle becomes less acute or straight as the puborectal muscle sling (p. 831) normally pulling it forward relaxes, facilitating the passage of faeces into the anal canal. A sitting posture also assists the reduction of the anorectal angle. The muscles of the pelvic floor including the external sphincter now relax, too, so that pelvic floor descends a little, and the muscles of the anterior abdominal wall and diaphragm contract to raise the intra-abdominal pressure. The internal and external anal sphincters then relax, and at the same time the anal canal shortens and widens (see Shafik 1986) due to the contraction of the longitudinal muscle of the conjoint longitudinal tract and recoil of related elastic tissue. Because of this shortening the lower end of the anal canal becomes everted so that during the peak of defaecation the lower border of the internal sphincter and thus the intersphincteric groove come to lie at the anal orifice, with the subcutaneous external sphincter now situated radially lateral to it. The internal surface of the canal also becomes everted so that its epithelial lining below the white line is presented at the body surface.

At the end of defaecation, the external and internal sphincters, puborectalis and perineal muscles contract again (the closing reflex), and these arrangements are reversed to restore the original length and shape of the anal canal, the anorectal angle and the closure of the anal orifice.

Innervation of anal muscles

The *internal sphincter* has an autonomic supply from sympathetic fibres running in the plexuses around the superior rectal artery and the hypogastric plexus; parasympathetic fibres enter from the pelvic splanchnic nerves (S2, 3, 4) (see also pp. 1282, 1297).

The motor supply of the *external sphincter* is from the inferior rectal branch of the pudendal nerve (S2, 3) and the perineal branch of the fourth sacral nerve (S4) (see also pp. 1282, 1288). *Puborectalis* has the same supply as the rest of levator ani, i.e. somatic motor axons from the fourth sacral nerve and the inferior rectal branch of the pudendal nerve (S2, 3, 4).

The conjoint longitudinal coat, being derived from the rectal smooth muscle and surrounding sphincters, shares their innervation.

The muscle co-ordination required for these complex activities depends on reflex control involving, for the smooth muscle of the internal sphincter, the enteric plexus and associated autonomic and visceral sensory nerves; for the skeletal muscle of the external sphincter, puborectalis and associated perineal muscles, regulation is partly reflex, and partly voluntary through the visceral and somatic afferents and somatic efferent nerves. Essential for all of these purposes are the rich sensory innervation of the rectal and anal canal linings, and proprioceptive fibres in the muscle and surrounding tissues (see p. 1781). Neural integration of these sensory inputs and appropriate motor control are performed at many levels in the nervous system including the spinal cord, brainstem, thalamus and cortex. These operations not only monitor and regulate the actual process of defaecation, but also engage in more subtle behaviours within the rectum and anal canal, e.g. in the separation of faeces from rectal gas, local adjustments to faecal consistency and quantities, self-cleansing movements in the rectum and anal canal and co-ordination with other actions of the perineal and abdominal muscles.

Dual embryonic origin of the anal canal

The anal canal is derived embryonically from two sources. The region above the anal valves arises from the endodermally-lined cloaca, whilst below this boundary it comes from the proctodeum, covered with ectoderm (see p. 191).

The cloacal part (above) is innervated by autonomic nerves; the arterial supply (Griffiths 1961) is mainly from the superior and middle rectal arteries, while the venous drainage is to the superior rectal vein, a tributary (via the inferior mesenteric vein) of the portal venous system. The lymphatics drain with those of the rectum (p. 1621).

The proctodeal part (below) is covered mainly by skin, and is hence innervated by spinal nerves (the inferior rectal), and its vasculature is also that of the body wall, namely the inferior rectal artery and vein, branches and tributaries of, respectively, the internal pudendal artery and vein. Likewise, the lymphatic drainage of this region joins that of the perianal skin and passes to the superficial inguinal lymph nodes.

The differing nerve supply of the two parts is apparent in the condition of haemorrhoids, which may be covered by skin inferiorly and mucosa superiorly; to thrombose these varicose veins by injec-

inserted i

wer part

Fissure in ano (tearing of anal valves) is very painful because it involves this lower part of the anal canal. In portal obstruction, the collateral circulation opened up by anastomosis between portal and system veins in the anal canal may cause these veins to dilate, predisposing to haemorrhage.

RECTAL EXAMINATION

On inserting the index finger through the anal orifice in rectal examination, the finger is first resisted by the subcutaneous external sphincter and then by the internal sphincter, superficial and deep parts of the external sphincter and the puborectalis; beyond this it may reach the inferior (or even middle) transverse rectal fold. Many structures related to the canal and lower rectum may be palpated.

In males through the anterior rectal wall (see **13.32**), the penile bulb and (particularly with a catheter in the urethra) the membranous urethra are first identified; about 4 cm from the anus the prostate can be felt and beyond this the seminal vesicles (if enlarged) and the base of the bladder (especially if distended). Posteriorly, pelvic surfaces of the lower sacrum and coccyx are palpable and laterally the ischial spines and tuberosities and (if enlarged) the internal iliac lymph nodes. Pathological thickening of the ureters, swellings in the ischiorectal fossa and abnormal contents of the rectovesical recess may also be detected.

In **females** the uterine cervix is palpable through the anterior rectal wall (see **14.15A**); its degree of dilatation during parturition may be assessed in this manner. Pathological conditions causing tenderness or changes in the shape, size, consistency or position of the ovaries, uterine tubes, broad ligaments and recto-uterine pouch may be detected.

In both sexes, tenderness of an inflamed vermiform appendix (if pelvic) can also be elicited.

RECTAL FASCIAE AND 'SPACES'

Parts of the pararectal pelvic fascia are composed of loose connective tissue, whilst others are denser, with particular orientations and attachments; the latter are often considered to be rectal 'supports' requiring surgical division to mobilize the organ. From the lower sacrum's anterior surface a strong avascular condensation proceeds to the posterior aspect of the anorectal junction (*fascia of Waldeyer*). Around the middle rectal vessels fascia extends from the posterolateral pelvic wall (level with the third sacral vertebra) to the rectum as the *lateral rectal ligaments*. Anteriorly, between the rectum and the seminal vesicles and prostate, the *rectovesical fascia* (p. 1859) is more loosely attached to the seminal vesicles and prostate than to the rectum and in rectal excision it must be separated from them.

In addition to the ischiorectal fossae (p. 832) several '*spaces*' of surgical importance are related to the rectum and anal canal. The *pelvirectal space* comprises the loose extraperitoneal connective tissue above the levator ani; it is divided into anterior and posterior regions by the *lateral rectal ligaments*. The *submucous space* of the anal canal is between the mucosa (above the white line) and the internal sphincter; it contains the superior part of the internal rectal venous plexus and lymphatics; above, it is continuous with the rectal submucosa, below with the *perianal space*, the lateral part of which is bounded above by the most lateral elastic septum traversing the subcutaneous part of the external sphincter. The septum divides the ischiorectal fossa into a superior part containing coarsely lobulated fat and a smaller, lower, perianal space containing fine, compact fat. The perianal space contains the subcutaneous part of the external sphincter, the external rectal venous plexus and terminal rami of the inferior rectal vessels and nerves. The radiating septa traversing the subcutaneous part of the external sphincter tend to divert pus in the perianal space to the anal canal at the white line or to the surface of the perianal skin, rather than to the main ischiorectal fossa. Since the perianal space surrounds the lower anal canal, pus on one side may spread around it.

MICROSTRUCTURE OF THE LARGE INTESTINE

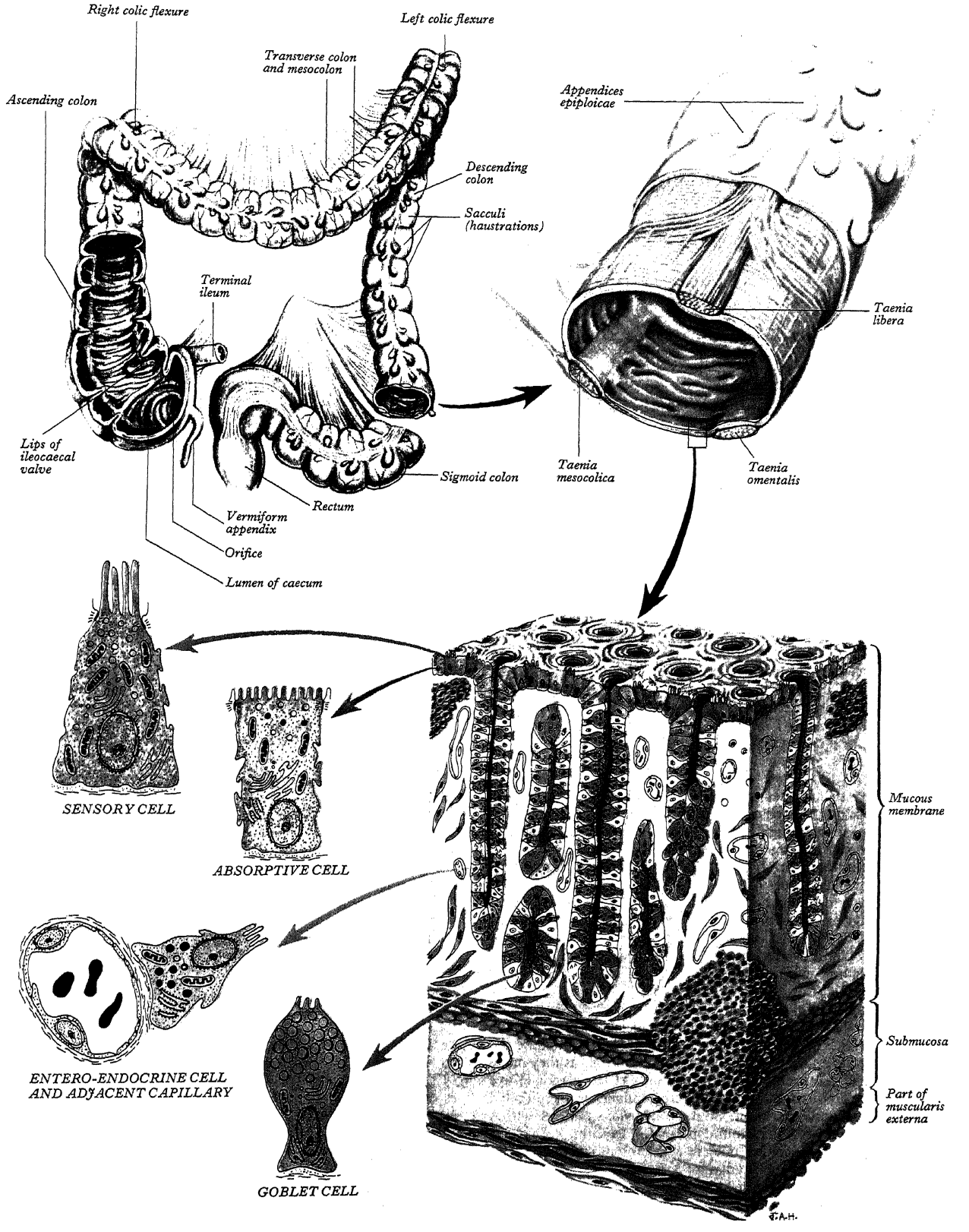
The layers of mural tissue in the large intestine (**12.82, 123**) resemble those in the small intestine (p. 1767), except that villi are absent. The microscopic appearance of the anal canal is described on p. 1780.

Mucosa

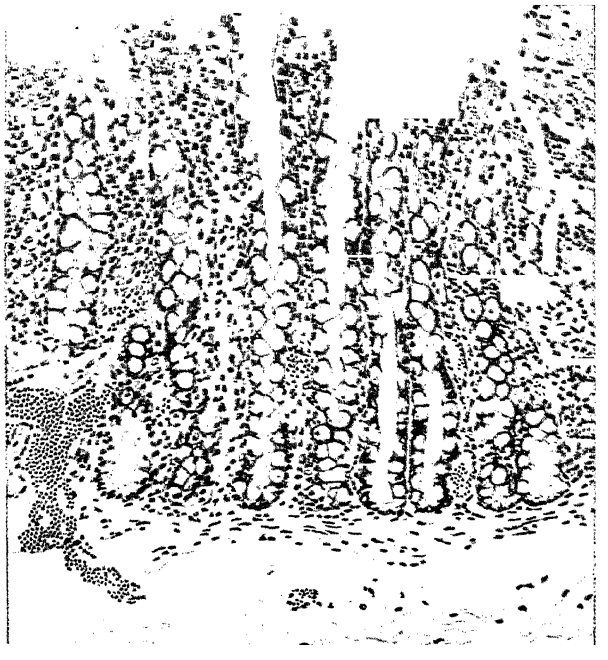
The mucosa is pale, smooth, and, in the colon, raised into numerous crescentic folds between the sacculi; in the rectum it is thicker, darker, more vascular, and more loosely attached to the submucosa.

Epithelium of the caecum, colon and upper rectum (**12.123–127**). This consists of the following at the luminal surface: columnar cells, mucous (goblet) cells, and occasional microfold cells (p. 1443) overlying lymphoid follicles. Columnar and mucous cells are also present in the intestinal glands which additionally contain stem and enteroendocrine cells (see below). Ultrastructural details of these cell types have been described by Pittman and Pittman (1966), Lorenzonn & Trier (1968), and may be summarized briefly as follows.

Columnar cells (vacuolar absorptive cells). These are the most numerous of the epithelial cell types; they are responsible for ionic exchange and other transepithelial transport activities in the colon, including ionic regulation and water resorption. Although there is some variation in their structure, they all bear apical microvilli, somewhat shorter and less regular than on small intestinal enterocytes, but otherwise similar in structural organization. Many of these cells also contain secretory granules in their apical cytoplasm; their secretion appears to be largely mucins, but is also rich in antibodies of the IgA type. All cells have typical junctional complexes around their apices, limiting extracellular diffusion from the lumen into the intestine wall.



12.123 Diagrams of the disposition of the major regions of the large intestine, the micro-architecture and histology of the colonic wall and the ultrastructure of its epithelial cells. Note the aggregations of lymphocytes (shown in yellow) and undifferentiated epithelial cells (shown in white).



12.124 Section of the mucous membrane of the feline large intestine. Note the presence of large numbers of goblet cells and the vascularity of the mucosa. Stained with haematoxylin and eosin. Magnification c. × 100.

Mucous cells (goblet cells). They resemble those of the small intestine, and they have a similar structure.

Microfold cells. Also similar to those of the small intestine, they consist of cells with long microvilli, lying over lymphoid follicles.

Stem cells. The source of the other epithelial cell types, they are located at or near the bases of the intestinal glands, undergoing periodic mitosis to give a stream of cells that migrate on to the luminal surface of the intestine and are shed (or otherwise disposed of) at the boundaries between individual glands (*extrusion zones*) (for details of kinetics, see Chang & Leblond 1971; Potten et al 1990)

Enteroendocrine cells (**12.**129). These are situated mainly at the bases of the glands, and secrete into the lamina propria. For further details see p. 1787.

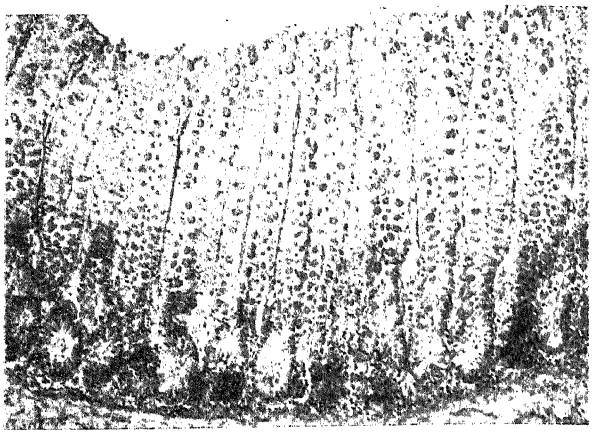
Brush cells. An infrequent type of columnar epithelial cell, also found in various other mucosal sites in the body, these cells have an apical bundle of long, straight microvilli giving them a characteristic appearance. Their functions are unknown (see also p. 69).

Intestinal glands (crypts) of the large intestine. Narrow perpendicular epithelial tubules of mucosal epithelium, they are longer, more numerous and closer together than those of the small intestine; their openings give a cribriform appearance to the mucosa in surface view (**12.**127). The glands are lined by short columnar epithelial cells, mainly goblet cells (**12.**123–125), between which are columnar absorptive cells and enteroendocrine cells, and at their bases, the epithelial stem cells (Lorenzonn & Trier 1968).

Lamina propria. This is composed of connective tissue which supports the epithelium. Surrounding the glands is a specialized zone of connective tissue forming a fibrous sheath around each; here the fibroblasts migrate apically alongside the epithelial cells as they move from the zone of cell proliferation in the bases of the glands (Kaye et al 1968); they are thought to have directive influences on epithelial cell proliferation and migration. Solitary *lymphoid follicles* within the lamina propria are most abundant in the caecum, vermiform appendix (p. 1776) and rectum, but are also present scattered along the rest of the large intestine (Langman & Rowland 1986). They are similar to those of the small intestine (p. 1771).

Muscular mucosae. Also resembling that of the small intestine, it has prominent longitudinal and circular layers, and some slips of muscle pass towards the intestinal lumen between the glands.

Submucosa. This too is like that of the small intestine.



12.125 Medium-power light micrograph of the rectal mucosa showing crypts containing goblet cells. Stained with alcian blue/light green. Magnification × 80. (Material provided by D Ristow, Department of Anatomy, UMDS, Guy's Campus, London.)

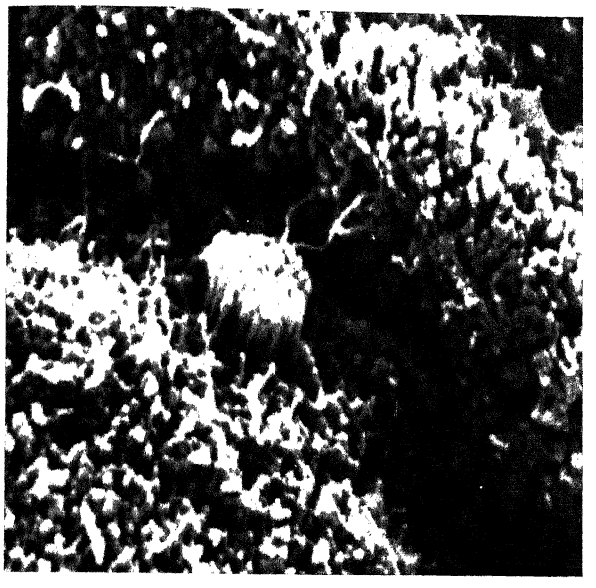
Muscularis externa

The muscularis externa has outer longitudinal and inner circular layers of smooth muscle. The longitudinal fibres form a continuous layer (Hamilton 1946) but are also aggregated as longitudinal bands or *taeniae coli* (**12.**96, 123), between which the longitudinal layer is less than half the circular layer in thickness. In the caecum and colon three taeniae appear, each varying from 6 to 12 mm in width. The *taenia libera* is anterior in the caecum, the ascending, descending and sigmoid colon, but inferior in the transverse colon. The *taenia mesocolica* is posteromedial in the caecum, the ascending, descending and sigmoid colon, but posterior in the transverse, being located at the attachment of the transverse mesocolon. The *taenia omentalis* is posterolateral in the caecum, the ascending, descending and sigmoid colon, but anterosuperior in the transverse colon, being located where the posterior (ascending) layers of the greater omentum meet this part of the large intestine. These bands are said to be shorter than the other intestinal layers, thus producing puckering or haustration of the caecum and colon into sacculi. When they are removed, the tube lengthens and loses its sacculation. In the descending colon the taeniae thicken at the expense of the rest of the longitudinal layer, while there is a real increase in its total bulk in the sigmoid colon, where the longitudinal fibres are more scattered. They form a layer which completely encircles the rectum, but are thicker on its anterior and posterior aspects, producing recognizable broad *anterior* and *posterior bands*. At the rectal ampulla a few strands of the anterior longitudinal fibres pass forwards to the perineal body (p. 833), as the *musculus recto-urethralis*. In addition, two fasciculi of smooth muscle pass antero-inferiorly from the front of the second and third coccygeal vertebrae to blend with the longitudinal muscle fibres on the posterior wall of the anal canal, forming the *rectococcygeal muscles* (Wesson 1951).

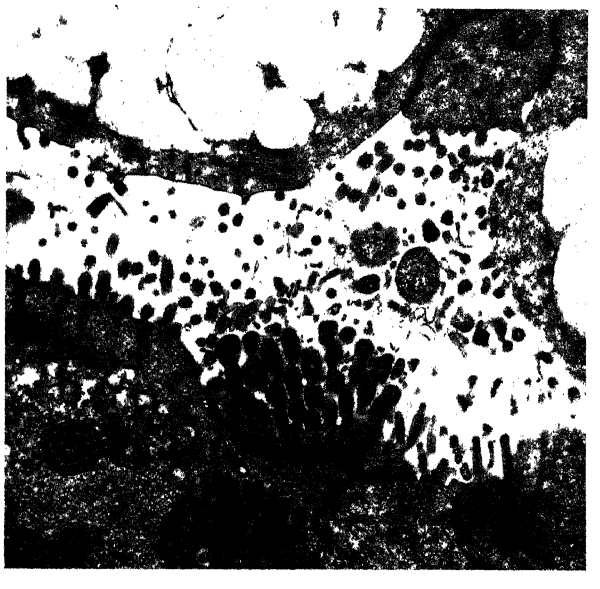
The circular fibres form a thin layer over the caecum and colon, aggregated particularly in the intervals between the sacculi; in the rectum they are a thick layer; in the anal canal they form the *sphincter ani internus*. Older observations of an interchange of fascicles between circular and longitudinal layers have been confirmed in a study of 112 cadavers (from early fetal life to 88 years); interchanges of fibres, especially near the taenia coli, are commonplace. Deviation of longitudinal fibres from the taeniae to the circular layer may, in some instances, explain the haustration of the colon (Pace 1968).

Serosa

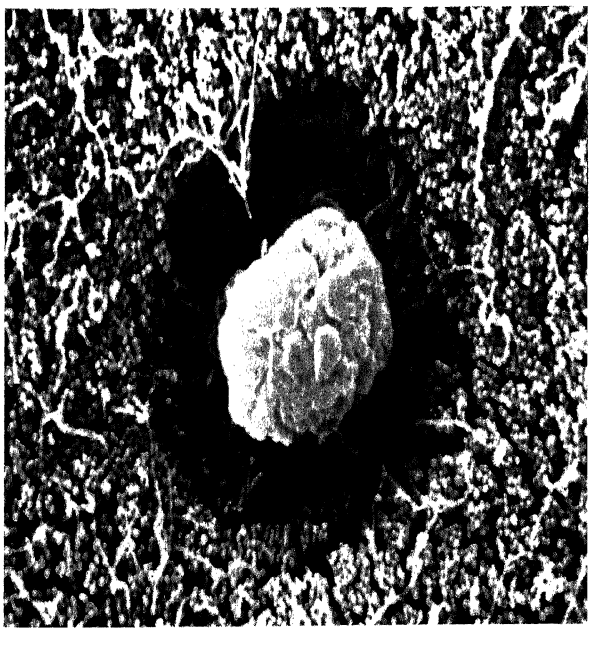
The serosa or visceral peritoneum is variable in extent. Along the colon the peritoneum forms small fat-filled *appendices epiploicae*, (**12.**80, 96, 123) most numerous on the sigmoid and transverse colon but generally absent from the rectum. Subserous loose connective tissue attaches the peritoneum to the muscularis externa.



A



B



C

The large intestine also provides an environment for a large population of bacteria, some of which are responsible for the metabolism of organic compounds to supplement vitamin intake, especially Vitamin B_{12} and vitamin K.

Because of the frequency of carcinomas of the large intestine, there has been some effort to characterize its normal and prepathological structure in mucosal biopsies for diagnostic and prognostic purposes. These have involved morphometric analysis of cell numbers, shapes, gland frequencies, connective tissue components and other features which show alterations related to proliferative rates and metaplasia leading to pathogenesis. For details see, e.g. Hamilton et al (1987); Tipoe et al (1992).

VESSELS OF THE LARGE INTESTINE

Arteries

Those which supply the parts of the large intestine derived from the midgut (caecum, appendix, ascending colon and right two-thirds of the transverse colon) are derived from colic branches of the superior mesenteric artery; those supplying hindgut derivatives (left part of the transverse, descending and sigmoid colon, rectum and upper anal canal) are derived from the inferior mesenteric (and its terminal branch, the superior rectal) and the middle rectal arteries (a branch of the internal iliac). Their large branches ramify between and supply the muscular layers, divide into small submucosal rami and enter the mucosa. A small contribution also comes from the median sacral artery which is the terminal midline branch of the aorta. Rectal and anal canal arteries are:

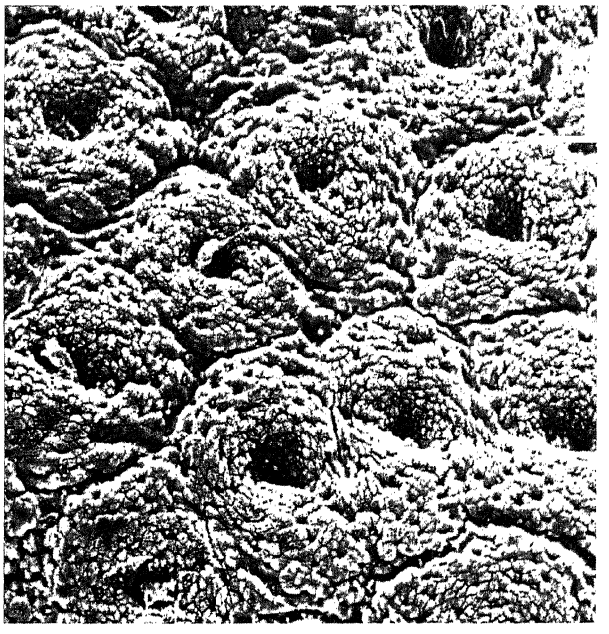
- The superior rectal (the continuation of the inferior mesenteric). This is the main rectal vessel, dividing into two branches descending one on each side of the rectum, their terminal branches piercing the muscular coat to enter the rectal submucosa and descend into the anal columns as far as the anal valves, where they form looped anastomoses.
- The middle rectal arteries which traverse the 'lateral rectal ligaments' to supply the muscle of the lower rectum, anastomosing freely with each other but forming only poor anastomoses with the superior and inferior rectal arteries.
- The inferior rectal arteries (from the internal pudendals), which supply the internal and external sphincters, the anal canal below its valves and the perianal skin.
- The median sacral artery which supplies the posterior wall of the anorectal junction and of the anal canal.

Veins

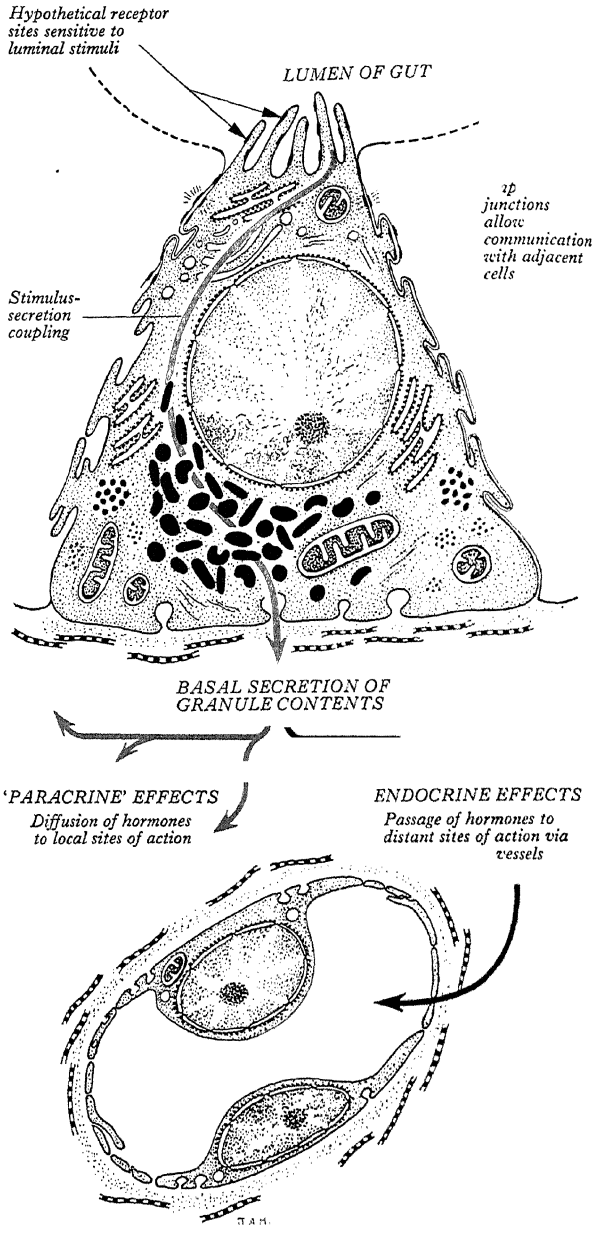
These are the superior and inferior mesenteric, draining the regions supplied by the corresponding arteries. The veins of the rectum and anal canal are:

- The superior rectal veins, which pass from the internal rectal plexus in the anal canal and ascend in the rectal submucosa as about six vessels of considerable size to pierce the rectal wall about 7.5 cm above the anus, uniting to form the superior rectal vein, which continues as the inferior mesenteric.
- The middle rectal veins, from the submucosa of the rectal ampulla which drain chiefly its muscular walls.
- The inferior rectal veins, which drain the external rectal plexus

12.126A, B, C A Scanning electron micrograph of the epithelium lining the colon (rat), showing a cell of suggested sensory function, bearing an apical tuft of particularly long microvilli. Magnification × 12 000. B Transmission electron micrograph showing part of a colonic epithelial cell bearing sensory microvilli. The smaller absorptive microvilli of adjacent cells can also be seen. Magnification × 14 000. C Scanning electron micrograph of the epithelium lining the colon (rat), showing a goblet cell surrounded by absorptive cells bearing microvilli. Magnification × 8000. (Prepared and photographed by Michael Crowder, Guy's Hospital Medical School, London.)



12.127 Scanning electron micrograph of the luminal surface of the human rectal mucosa. The outlines of cells bearing microvilli and the openings of rectal crypts can be seen. Magnification × 240. (Material supplied by D S Rampton; prepared and photographed by Michael Crowder, Guy's Hospital Medical School, London.)



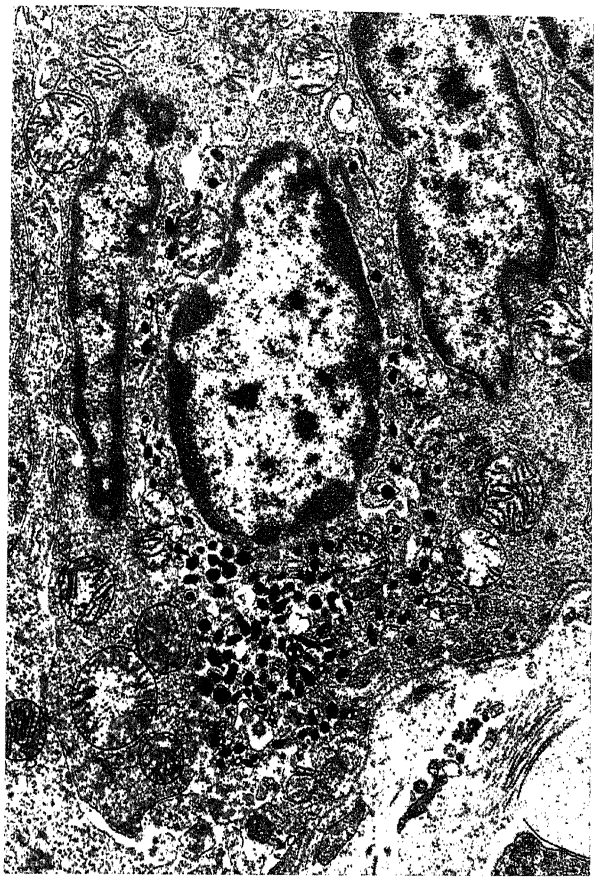
12.128 Diagram showing the ultrastructure and possible modes of action of an entero-endocrine cell.

Anastomoses occur between portal and systemic veins in the wall of the anal canal (p. 1604).

INNERVATION

Except in the lower anal canal, this is sympathetic and parasympathetic. The caecum, appendix, ascending colon and right two-thirds of the transverse colon (derivatives of the midgut) have a sympathetic supply from the coeliac and superior mesenteric ganglia, and a parasympathetic supply from the vagus; the nerves are distributed in plexuses around the rami of the superior mesenteric artery. The left third of the transverse colon, the descending and sigmoid colon, rectum and upper anal canal (derivatives of the hindgut) take their sympathetic supply from the lumbar part of the trunk and the superior hypogastric plexus by means of periarterial plexuses on rami of the inferior mesenteric artery. The sympathetic supply of the colon is largely vasomotor. The parasympathetic supply is from the pelvic splanchnic nerves (nervi erigentes), from which rami pass to the inferior hypogastric plexuses to supply the rectum and upper half of the anal canal: some fibres ascend through the superior hypogastric plexus to accompany the inferior mesenteric artery to the transverse, descending and sigmoid colon (p. 1308). Rami of the pelvic splanchnic nerves ascend on the posterior abdominal wall behind the peritoneum, independently of the inferior mesenteric artery, to be distributed directly to the left colic flexure and descending colon (Mitchell 1953). The ultimate distribution in the wall of the large intestine is as in the small intestine (p. 1772). Adrenergic and cholinergic activity in the nerve supply of the taenia coli, and distribution of the nerve fibres, suggest that (in guinea-pigs) few smooth muscle cells are directly innervated, propagation of excitation being chiefly through gap junctions between them (Bennett & Rogers 1967).

Sympathetic nerves to the rectum and upper anal canal pass mainly along the inferior mesenteric and superior rectal arteries and partly via the superior and inferior hypogastric plexuses, the latter supplying the lower part of the rectum and the internal anal sphincter. Parasympathetic rami from the pelvic splanchnic nerves (S2, 3, 4) pass forwards as long strands (about 3 cm long) from the sacral nerves to join the inferior hypogastric plexuses on the sides of the rectum, being motor to the rectal musculature and inhibitory to the internal anal sphincter. The external sphincter ani is supplied by the inferior rectal branch of the pudendal nerve (S2, 3) and the perineal ramus of the fourth sacral nerve (p. 1149). In rectal surgical excision, dissection must be kept close to its wall to avoid damage to these nerves with consequent bladder dysfunction and, in males, loss of penile erection. Afferent impulses mediating sensations of distension pass in afferent fibres in the parasympathetic nerves, pain impulses in the sympathetic *and* parasympathetic nerves supplying the rectum and the upper part of the anal canal. In colonic *aganglionosis (megacolon)* postganglionic neurons of the enteric nervous system (p. 1749) are reduced or absent in the colonic wall; Soltero-Harrington et al 1969). Garrett et al (1969) have studied the myenteric plexus and ganglionic neurons by electron microscopy and histochemical techniques for transmitter substances, reporting that in megacolon a variable diminution and sometimes absence of ganglion cells occurred, but that innervation of the muscle layers was defective even when ganglionic neurons were present.



12.129 Transmission electron micrograph of an entero-endocrine (APUD) cell of the epithelium lining the colon (rat). Secretory vesicles can be seen towards the basal aspect of the cell. Absorptive columnar cells lie on either side of the APUD cell. Magnification × 11 000. (Prepared and photographed by Michael Crowder, Guy's Hospital Medical School, London.)

Lymph nodes and vessels

These are described on page 1621.

GASTRO-ENTERO-PANCREATIC ENDOCRINE SYSTEM (12.128–130)

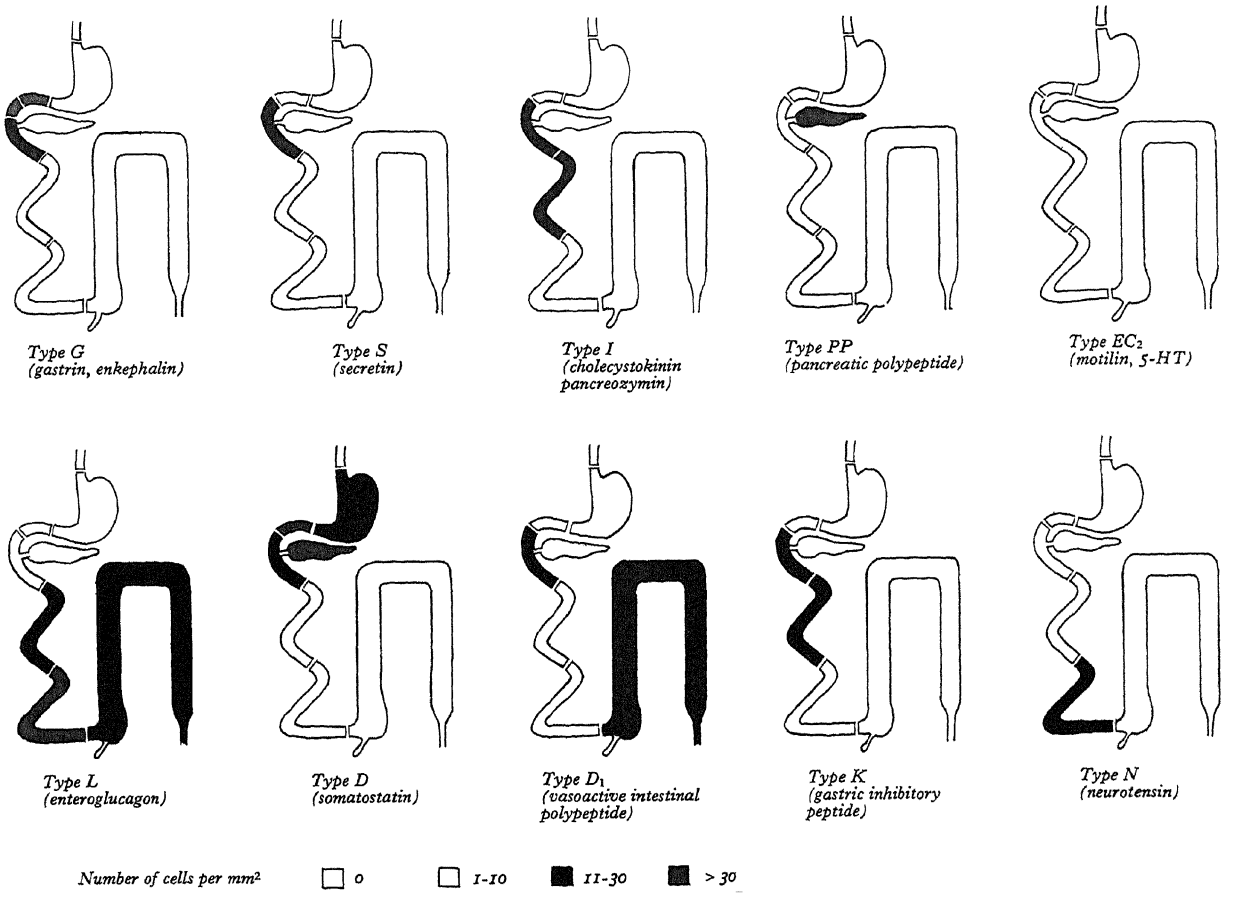
The gastro-entero-pancreatic (GEP) endocrine (or enteroendocrine) system (Fujita 1973) consists of scattered, often solitary, hormone-producing cells of the gastrointestinal mucosa and pancreas.

The ultrastructure of human GEP endocrine cells has been detailed by Rubin (1972), Sasagawa et al (1973), Capella et al (1976) and Cavallero et al (1976) and summarized by Solcia et al (1981). Endocrine cells are scattered in the gastrointestinal mucosa, with their bases resting on the basal lamina. Their secretory granules vary in shape, size and ultrastructure in the different cell types, being usually infranuclear, while the Golgi complexes are supranuclear; luminal aspects of 'open' cells display microvilli of variable number, length and shape. Typical enteroendocrine cells are shown in (**12.**128, 129). Human *P cells* contain very small (100–140 nm) secretory granules slightly reactive to Grimelius' silver stain (Capella et al 1977); rare in normal adult tissues, they may contain a bombesin-like polypeptide (Polak et al 1976). *EC cells*, which contain osmiophilic, argentaffin, Grimelius' silver-reactive granules, are classified as EC_1, and EC_2 and EC_n; in addition to 5-hydroxytryptamine, the EC_1 cells store substance P (SP), EC_2 cells store motilin (Polak et al 1976) and EC_n cells an unidentified material. The *D_1 cells* contain argyrophilic granules about 140–190 nm in diameter (Capella et al 1977) and store a VIP-like material. *PP cells*, common in the pancreatic islets but rare in the exocrine pancreas, store pancreatic polypeptide in granules of 150–170 nm; they are equivalent to F cells identified in other mammals (Baetens et al 1976). Human *D, B* and *A cells* are described with the endocrine pancreas (p. 1791). *X cells*, identified in human oxyntic mucosa by Solcia et al (1977), are of unknown function. Human *ECL cells* (Vassallo et al 1971) store a reducing amine, possibly 5-hydroxytryptamine, in granules with intensely argyrophilic cores; histamine may also occur. Human *G cells* (Vassalo et al 1971) manufacture gastrin and possibly enkephalin (Polak et al 1978), and have slightly argyrophilic granules with floccular contents. *S cells* (Capella et al 1976) are scattered in duodenojejunal mucosa and produce secretin (Larsson et al 1977); they are similar to D_1 cells but differ in their secretory product. Human *I cells* (Capella et al 1976), commonest in the duodenum and jejunum but rare in the ileum, are sources of cholecystokinin-pancreo-zymin (pancreaticozymin) (Buchan et al 1977). Human *K cells* (Capella et al 1976) contain large granules (approximately 350 nm in diameter) with osmiophilic, argyrophobic cores; like I cells, they are commonest in the duodenum and jejunum. K cells produce gastric inhibitory peptide. Human *N* and *L cells* are difficult to distinguish cytologically; granules of N cells are, however, generally homogeneous and about 300 nm in diameter, while those of L cells sometimes have argyrophilic cores and tend to be smaller (about 260 nm). N cells produce neurotensin (Orci et al 1976), L cells enteroglucagon or glicentin.

Concentrations of endocrine cells in the gastrointestinal mucosa are low and generally decrease progressively in an anal direction (**12.**130).

Certain common features of GEP endocrine cells allow other classifications. They all produce peptides and/or amines active as hormones or neurotransmitters and contain neuron-specific enolase, an isoenzyme of the glycolytic enzyme enolase (Polak et al 1980). They thus belong to the amine precursor uptake and decarboxylation *(APUD) cell series* (Pearse 1968, 1976, 1980) and modulate not only autonomic activity but also each other (**12.**130). The APUD concept is detailed elsewhere (p. 1899). The discovery of supposedly similar neurohormones and neurotransmitter peptides in cerebral neurons and some GEP endocrine cells, with other neuronal characteristics of the latter, has led to their designation as *paraneurons* (Fujita 1976). Peptides common to brain and gastrointestinal mucosa include: SP, somatostatin, VIP, bombesin, neurotensin, cholecystokinin (CCK) and the opiatoid enkephalin (Bloom & Polak 1978). GEP endocrine cells are presumed to have superficial receptor sites, stimulation of which by 'secretogogues' triggers stimulus-secretion coupling (Kanno 1973), as in chromaffin cells (Douglas 1968); they can thus also be termed *receptosecretory cells* (Fujita 1976).

The route of action of endocrine cells restricted to the gastrointestinal mucosa remains in doubt. Their ultrastructure and proximity to capillaries suggest that their secretory products are endocrinal, exerting distant, diffuse effects via the blood. However, of their many products, only the following have been shown to act as circulating hormones: gastrin, secretin, cholecystokinin-pancreozymin, gastric inhibitory peptide, motilin and enteroglucagon (Bloom & Polak 1978). Basic differences exist between endocrine cells in gastric and intestinal mucosae and those in most other endocrine organs: they are not aggregated into glands but scattered among their local targets; most are close to the alimentary lumen, allowing their specialized plasma membranes to detect and respond to luminal stimuli; there are no common hyposecretory or hypersecretory syndromes; relations between plasma hormone levels and functional response (e.g. modulation of neural control of gut motility) is not stoichiometric. Wingate (1976) has suggested that gastrointestinal hormones may have local 'paracrine' **and** distant 'endocrine' effects; direct actions on gastrointestinal smooth muscle, on adjacent endocrine cells, on other enterocytes and on local neurons are speculative but possible. Although the gut might be regarded as the largest endocrine organ (Pearse 1974), it is perhaps more properly regarded as a region in which neural, paracrine and endocrine controls of activity are intimately linked.



12.130 Approximate quantitative distribution of a selection of human gastro-entero-pancreatic (GEP) endocrine cells (highly diagrammatic, after Bloom & Polak 1978, with permission from Churchill Livingstone).

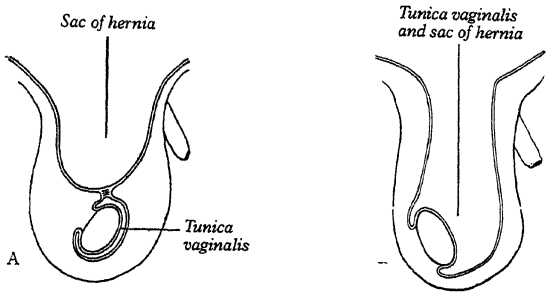
The rarity of rupture of the jejunum and ileum by external injury is due to their elasticity and mobility; the more fixed duodenum, particularly its horizontal part across the vertebral column, is more vulnerable. In external hernia the ileum is most frequently involved; in the large intestine it is usually the caecum or sigmoid colon. Omentum commonly protrudes into the hernia sac. Other abdominal viscera may rarely be involved (e.g. appendix, stomach, Meckel's diverticulum). The chief sites of hernia are inguinal, femoral and umbilical.

INGUINAL HERNIA

Here a viscus is protruded through the inguinal region of the abdominal wall. The principal varieties are oblique and direct.

OBLIQUE (INDIRECT) INGUINAL HERNIA

Here the involved viscus is pushed through the lateral inguinal fossa (behind the deep inguinal ring), preceded by a pouch of parietal peritoneum and extra-peritoneal connective tissue. It enters the inguinal canal at its deep ring and is invested by internal spermatic fascia enclosing the spermatic cord. As it traverses the canal it pushes up the arching fibres of transversus abdominis and obliquus internus, is covered by the cremasteric fascia and muscle and lies anterior to the cord. Emerging at the superficial inguinal ring, it is invested by the external spermatic fascia and also, as it descends into the scrotum, by superficial fascia and skin. The hernia may become constricted at the deep ring, with interference to its blood supply (strangulation). When this is relieved the deep ring should be cut superolaterally to avoid the inferior epigastric vessels. Most oblique inguinal hernias follow congenital defects in the processus vaginalis (p. 212). Obliteration of this may be complete at birth or it may begin late and be completed only after birth; closure begins at the deep inguinal ring and epididymal head, extending until all of the intervening region becomes a fibrous cord. Complete or partial failure of closure of the processus entails variations in the relation of the hernial protrusion to the testis and tunica vaginalis; e.g. if the processus is fully patent, the herniated gut descends in front of the testis into the tunica vaginalis (*complete congenital hernia*); in this case, the processus and tunica form the hernial sac. In *incomplete congenital hernia* (hernia into the funicular process), the herniating gut descends to the top of the testis, where the processus is sealed off from the tunica vaginalis (**12.**131A, B). Although the above types are called congenital, actual extrusion into a pre-existing peritoneal sac may not occur until adult life and then be produced by an increased intra-abdominal pressure or sudden muscular strain. (For a critique of the anatomy of inguinal hernia consult Lytle 1979.)



Diagrams representing varieties of oblique inguinal hernia: A incomplete congenital; B complete congenital.

DIRECT INGUINAL HERNIA

Here the protrusion is through some part of the inguinal triangle, which is bounded inferiorly by the medial half of the inguinal ligament, medially by the lower lateral border of rectus abdominis and laterally by the inferior epigastric artery. It overlies the medial inguinal fossa and, partly, the supravesical fossa (p. 1737). A direct hernia is through either:

- the *medial inguinal fossa*, where only extraperitoneal tissue and transversalis fascia separate the peritoneum from the aponeurosis of the external oblique or
- the *supravesical* fossa and *falx inguinalis* (conjoint tendon), which lies in front of the fossa.

In the first form, herniation is lateral to the conjoint tendon, propelling before it the peritoneum, extraperitoneal tissue and transversalis fascia to enter the inguinal canal, which it traverses to emerge from the superficial ring, covered by external spermatic fascia. Its coverings are like those of the oblique form, except that a part of the general layer of transversalis fascia replaces the internal spermatic fascia, the hernia being between the innermost and middle coverings of the spermatic cord. In the second, more frequent form, the hernia is either between the fibres of the falx inguinalis, or the falx is gradually distended to form a complete covering. The hernia thus enters the lower end of the canal, escapes at the superficial ring medial to the cord and is covered by external spermatic fascia, superficial fascia and skin. Its coverings differ from those of oblique hernia, the conjoint tendon replacing the cremaster and part of the transversalis fascia replacing the internal spermatic fascia. In all varieties the most superficial covering is the external spermatic fascia, the outermost covering of the cord. An oblique inguinal hernia is within the cord, sharing all its coverings; a direct hernia acquires an additional covering from the transversalis fascia.

Direct inguinal hernia occurs usually in males. Its neck is typically wide, so that strangulation is rare in males. Its main peculiarities are:

- it is sited above the body of the pubic bone
- the inferior epigastric artery is *lateral* (not medial) to the neck of the sac
- the spermatic cord is posterolateral, not directly posterior as in oblique hernia.

A direct hernia is always of the acquired type. The stricture in both varieties of direct hernia is usually at the neck of the sac or at the superficial ring. Where the conjoint tendon is split, constriction may occur at the edges of the fissure. In all cases of inguinal hernia, whether oblique or direct, it is correct to divide the stricture upwards, parallel to the inferior epigastric artery to avoid damaging that vessel.

FEMORAL HERNIA

A femoral hernia protrudes through the femoral ring (p. 1737), which is normally closed by a femoral septum of modified extra-peritoneal tissue and is therefore a weak spot, especially in females, where the ring is larger and subject to profound changes during pregnancy. Femoral hernia is hence more common in women. When a section of intestine bulges through the ring, it pushes out a hernial sac of peritoneum. It is covered by extraperitoneal tissue (the femoral septum) and descends along the femoral canal to the saphenous opening, where it is prevented from descending along the femoral sheath by the narrowing of the latter, by the vessels and by the close attachment of the superficial fascia and sheath to the lower part of the rim of the saphenous opening (p. 873). The hernia hence turns forwards, distending the cribriform fascia and curving upwards over the inguinal ligament and the lower part of the external oblique aponeurosis. While in the canal the hernia is usually small, due to the resistance of its surrounds; but with escape into the inguinal loose connective tissue it enlarges. Thus a femoral hernia first descends, then ascends forwards; hence pressure to reduce it should be directed in the reverse order, with the thighs passively flexed for greatest relaxation.

Covering a femoral hernia are (from within outwards): the peritoneum, femoral septum, femoral sheath, cribriform fascia, superficial fascia and skin. A fibrous covering, the *fascia propria*, just outside the peritoneal sac but frequently separated from it by adipose tissue, may easily be may resemble a lipoma, but dissection will reveal the true hernial sac in its centre. The fascia propria is merely a femoral septum thickened to form a membranous sheet by hernial pressure. The intestine reaches only to the saphenous opening in *incomplete femoral hernia* in contradistinction to *complete hernia* where it passes through the opening. The small size of an incomplete hernia renders it difficult to detect and therefore dangerous, especially in the corpulent. The site of strangulation varies: it may be at the hernial sac's neck; more often it is at the junction of the falciform margin of the saphenous opening with the free edge of the pectineal part of the inguinal ligament; or it may be at the saphenous opening (p. 873). The stricture should be divided superomedially for a distance of 4–6 mm to avoid all normally positioned vessels and other important structures. (However, an abnormal obturator artery may be a complication, see p. 1560).

The pubic tubercle is an important landmark in distinguishing inguinal from femoral hernias; the hernia's neck is superomedial to it in inguinal hernia but inferolateral in the femoral form.

UMBILICAL HERNIA

There are three varieties of umbilical hernia.

CONGENITAL UMBILICAL HERNIA

This is due to the failure of retraction of the umbilical loop of the gut (p. 190)

INFANTILE UMBILICAL HERNIA

This is due to stretching of umbilical scar tissue, usually within 3 years of birth, and is associated with increased intra-abdominal pressure.

ACQUIRED UMBILICAL HERNIA

Really this is a hernia through the linea alba, usually just above the umbilicus (para-umbilical hernia); it occurs most frequently in obese multiparous females.

Rarely, hernia may occur at other sites, e.g. through the *lumbar triangle* (p. 837),

obturator foramen, greater or *lesser sciatic foramen* or *ischiorectal fossa. Incisional hernia* may occur at the sites of abdominal scars, particularly if the wound becomes infected. For further details of hernia and related surgical anatomy, see Chevrell (1987); for variations of medical and surgical importance in the small intestine and also in the colon consult Goligher (1967) and Kanagasuntheram (1970).

(12.96, 132–137)

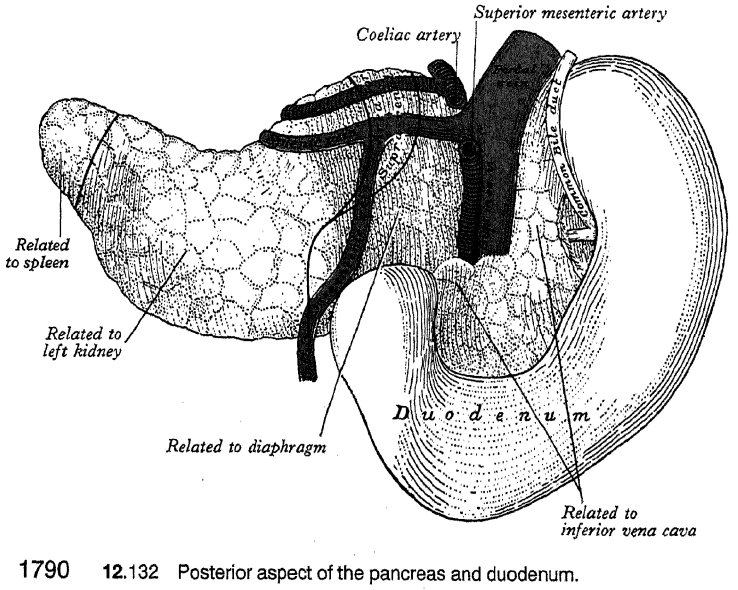
The pancreas is a soft, lobulated, greyish-pink gland, 12–15 cm long, extending nearly transversely across the posterior abdominal wall from the duodenum to the spleen, behind the stomach. Its broad, right extremity or *head* is connected to the *body* by a slightly constricted *neck*; its narrow, left extremity is the *tail*. It ascends slightly to the left in the epigastric and left hypochondriac regions.

RELATIONS OF THE PANCREAS

The structures related to the pancreas are best considered with respect to its different parts (**12.96**, 132, 133, 134), as follows.

Head. Flattened anteroposteriorly, it lies within the duodenal curve. Its upper border is overlapped by the superior segment of the duodenum, the other borders being grooved by the adjacent margin of the duodenum, which they variably overlap in front and behind. Sometimes a small part of the head is actually embedded in the wall of the descending part of the duodenum. From the lower and left part of the head the hook-like *uncinate process* projects upwards and to the left behind the superior mesenteric vessels. In or near the groove between the duodenum and the right and lower borders of the head are the anastomosing superior and inferior pancreaticoduodenal arteries (pp. 1549, 1553).

Anterior surface. From the pancreatic head's anterosuperior aspect the neck juts forwards, upwards and to the left, merging with the body. The boundary between head and neck, on the right and in front, is a groove for the gastroduodenal artery; on the left and behind it is a deep incisure containing the union of the superior mesenteric and splenic veins to form the portal vein. Below and to the right of the neck, the head's anterior surface is at first in contact with the transverse colon, separated only by loose connective tissue; still lower the surface is covered by peritoneum continuous with the inferior layer of the transverse mesocolon (**12.75**), and is in contact with the jejunum. The uncinate process is crossed anteriorly by the superior mesenteric vessels.



1790 **12.132** Posterior aspect of the pancreas and duodenum.

Posterior surface. The head is related posteriorly to the inferior vena cava which ascends behind it and covers almost all of this aspect; it is also related to the terminal parts of the renal veins and the right crus of the diaphragm. The uncinate process lies in front of the aorta. The bile duct is lodged either in a superolateral groove on the posterior surface or in a canal within the gland's substance (p. 1810).

Neck. About 2 cm long, it projects forwards, upwards and to the left from the head, merging into the body. Its anterior surface, covered with peritoneum, adjoins the pylorus, with part of the omental bursa intervening; the gastroduodenal and anterior superior pancreaticoduodenal arteries descend in front of the gland to the right of the junction of the neck and head; the posterior surface is related to the superior mesenteric vein and the beginning of the portal vein.

Body. Prism-like in section, it has three surfaces: anterior, posterior and inferior (more precisely anterosuperior, posterior and anteroinferior; they are obliquely set).

Anterior surface. This faces anterosuperiorly, is covered by peritoneum continuous antero-inferiorly with the *anterior* ascending layer of the greater omentum (**12.75**) and is separated from the stomach by the omental bursa. On reaching the taenia mesocolica, the greater omentum's *posterior* ascending layer fuses with the anterosuperior surface of the transverse mesocolon, while the anterior layer continues up to the mesocolon's root and is then reflected up over the anterior surface of the pancreas.

Posterior surface. Devoid of peritoneum, it is in contact with the aorta and the origin of the superior mesenteric artery, the left crus of the diaphragm, left suprarenal gland and with the left kidney and renal vessels, particularly the vein. It is closely related to the splenic vein which courses from left to right and separates it from the structures mentioned. The left kidney is also separated from the perirenal fascia and fat.

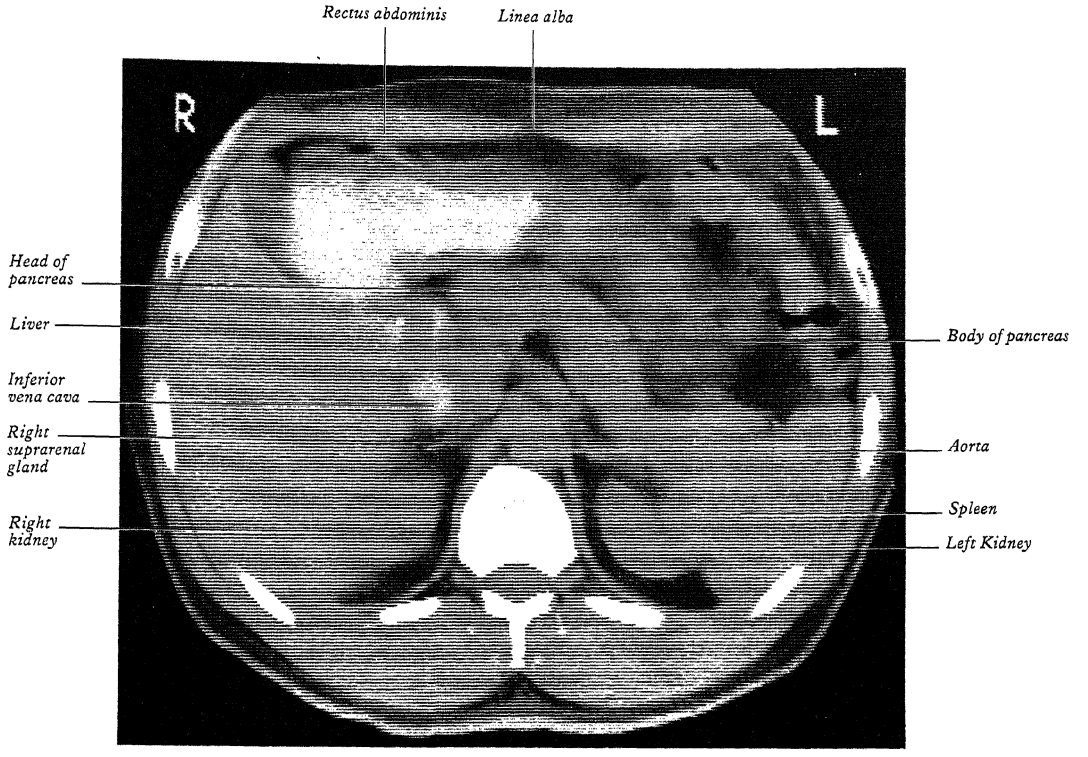
Inferior surface. This is narrow on the right but broadens to the left and is covered by the peritoneum of the postero-inferior layer of the transverse mesocolon; inferior to it are the duodenojejunal flexure and coils of the jejunum; its left end rests on the left colic flexure.

Superior border. This is blunt and flat to the right, but narrow and sharp to the left near the tail. An *omental tuberosity* usually projects from the right end of the superior border above the level of the lesser curvature of the stomach, in contact with the posterior surface of the lesser omentum. The border is related above to the coeliac artery, its common hepatic branch coursing to the right just above the gland, while its sinuous splenic ramus runs to the left

Anterior border. This separates the anterior from the inferior surfaces and along this border the two layers of the transverse mesocolon diverge, one passing up over the anterior surface, the other backwards over the inferior surface.

Inferior border. This separates the posterior from the inferior surfaces, the superior mesenteric vessels emerging from under its right extremity.

Tail. Narrow, usually reaching the inferior part of the gastric surface of the spleen, it is contained between the two layers of the splenorenal (lienorenal) ligament, together with the splenic vessels.



12.133 Computed tomogram of the abdomen in the transverse plane at the level of the pancreas. (Supplied by Shaun Gallagher, Guy's Hospital; photography by Sarah Smith, UMDS, Guy's Hospital Campus, London.)

Main pancreatic duct. It traverses the gland from left to right, being nearer its posterior than its anterior surface (**12.**134). It begins by the junction of lobular ducts in the tail and, running to the right in the body, receives further lobular ducts which join it almost at right angles (a 'herringbone pattern'). Much enlarged, it reaches the neck of the gland, turning down, backwards and right towards the bile duct, which lies on its right side. The two ducts enter the wall of the descending part of the duodenum obliquely and unite in a short dilated *hepatopancreatic ampulla* or ampulla of the bile duct (p. 1810); the narrow distal end of this opens on the summit of the *major duodenal papilla*, which lies posteromedial in this part of the duodenum, and 8–10 cm distal to the pylorus. Usually the two ducts do not unite until very near the orifice on the major papilla. Sometimes they open separately. Frequently an *accessory pancreatic duct* drains the lower part of the head (**12.**134), ascending in front of the main duct, with which it communicates, and opening on a small rounded *minor duodenal papilla*, about 2 cm anterosuperior to the major. The duodenal end of the accessory duct may fail to expand; secretion is then diverted along the connecting channel into the main duct (Dawson & Langmann 1961).

Surface anatomy (12.98).

The head of the pancreas lies within the duodenal curve. The neck is situated in the transpyloric plane, behind the pylorus. The body passes obliquely up and left for about 10 cm, its left part lying a little above the transpyloric plane. The tail is a little above and to the left of the intersection of the transpyloric and left lateral planes.

PANCREATIC MICROSTRUCTURE (12.134–137)

The pancreas is composed of two different types of glandular tissues in intimate association with each other. The main mass is *exocrine*, embedded in which are *pancreatic islets* of *endocrine cells*.

Exocrine pancreas

The exocrine pancreas is a branched acinar (acinoracemose) gland, surrounded and incompletely lobulated by delicate loose connective tissue (de Reuck & Cameron 1962; Beck & Sinclair 1971). Its pyramidal, acinar, secretory cells are arranged in flask-shaped or tubular groups. A narrow intercalated (intralobular) duct lies in each secretory mass, the initial parts of its walls being lined by cuboidal *centro-acinar cells*, later replaced by taller cuboidal and eventually columnar cells more distally. Larger, interlobular ducts are surrounded by loose connective tissue containing smooth muscle and autonomic nerve fibres. Enteroendocrine cells (p. 195) are present amongst the undifferentiated columnar ductual cells; mast cells are numerous in the surrounding loose connective tissue.

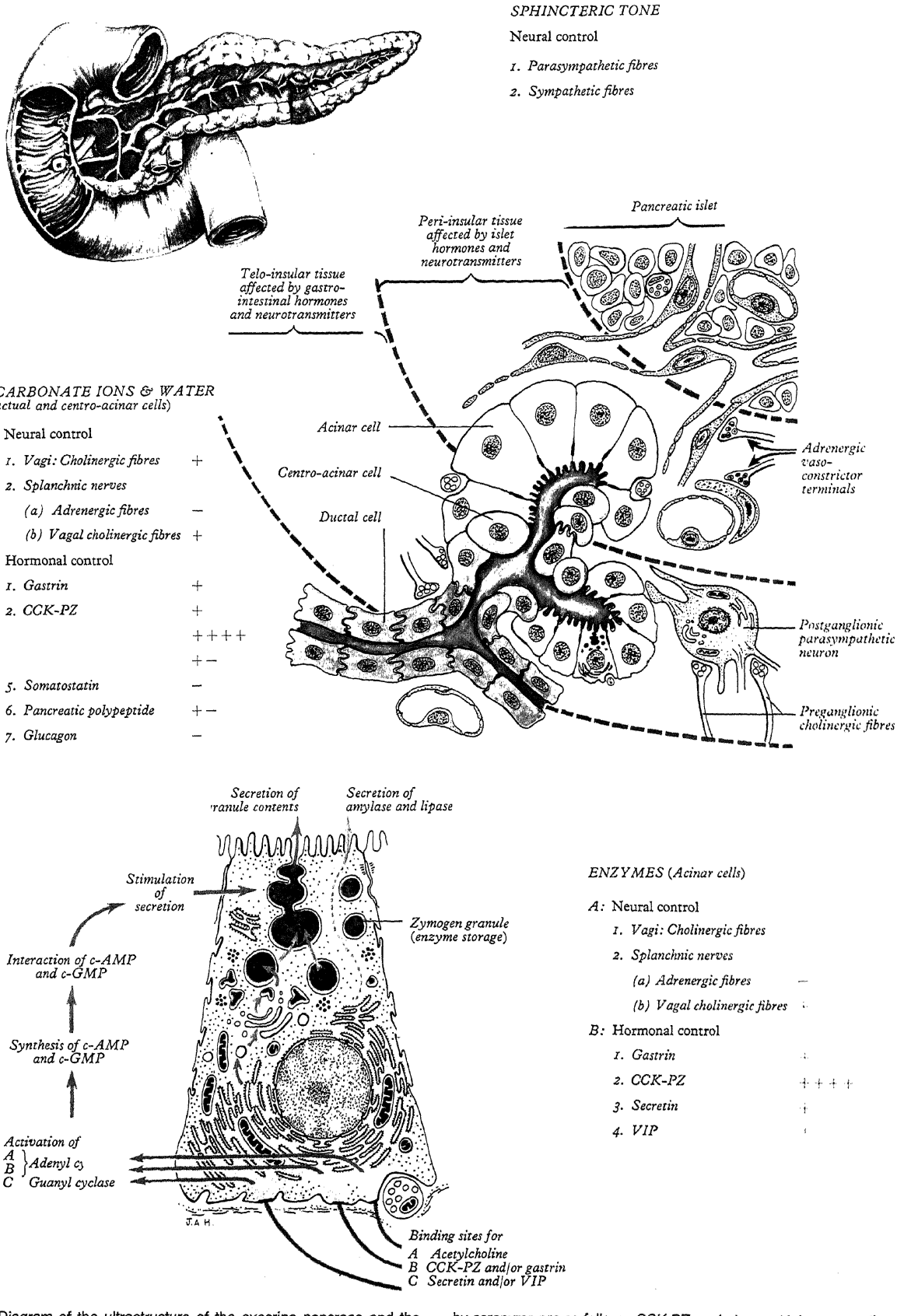
Acinar cells. Typical zymogenic cells, they have a basal nucleus and basophilic cytoplasm consisting of regular arrays of granular endoplasmic reticulum with mitochondria and dense secretory granules. A prominent supranuclear Golgi complex is surrounded by many larger, membranous granules containing the enzymic constituents of pancreatic secretion, only active after release. The orderly contents of the acinar cells have provided a widely used model for the investigation of routes of secretory synthesis and transport in protein-secreting cells at large (p. 30). After death, the action of pancreatic hydrolytic enzymes rapidly obscures cellular detail.

Ganglionic neurons (**12.**136) and cords of undifferentiated epitheliocytes also appear in the exocrine pancreas; the latter may provide stem cells for replacement of exocrine and perhaps endocrine cells. The structure of the exocrine pancreas and its control are summarized in **12.**134. For further details consult Webster et al (1977), Singh and Webster (1978), Case (1979) and Wormsley (1979).

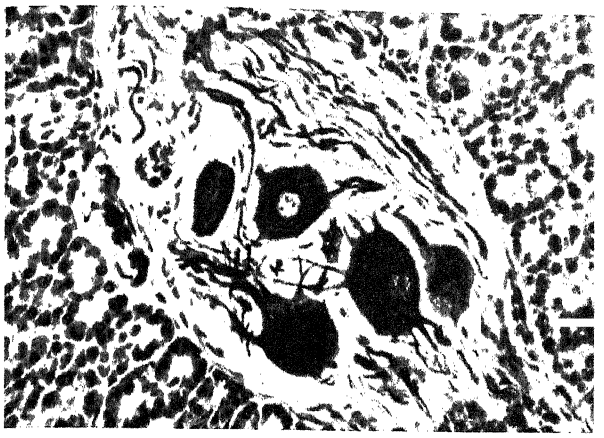
Endocrine pancreas (12.135, 137)

This consists of *pancreatic islets* or *insulae* (of Langerhans), composed of spheroidal or ellipsoidal clusters of cells dispersed in the exocrine tissue (Laguesse 1906; Lane 1907), together with scattered, often solitary, endocrine cells (Heitz et al 1976).

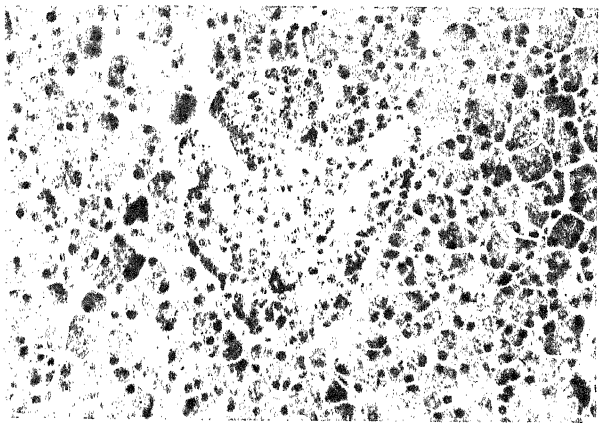
The human pancreas may contain more than a million islets, usually most numerous in the tail (Findlay & Ashcroft 1975). Each is a mass of polyhedral cells pervaded by fenestrated capillaries (Goldstein & Davies 1968) and a rich autonomic innervation (Gerich & Lorenzi 1978). Staining procedures distinguish three major



12.134 Diagram of the ultrastructure of the exocrine pancreas and the mechanisms by which its secretion is controlled. The hormones referred to by acronyms are as follows: CCK-PZ = cholecystokinin-pancreaticozymin; VIP = vaso-active intestinal polypeptide.



12.135 A low-power micrograph showing a cluster of autonomic ganglionic neurons with dendritic trees and axonal bundles, situated amongst pancreatic acinar cells of the goat. Palmgren silver impregnation. (Provided by J Henderson, Department of Physiology, Guy's Hospital Medical School, London.)



12.136 An islet of Langerhans and surrounding exocrine glandular tissue in the pancreas of a rhesus monkey, stained with orange G and aldehyde fuchsin. Within the islet, the B cells stain purple, whereas the A cells are pale yellow in colour. (Provided by J Henderson, Department of Physiology, Guy's Hospital Medical School, London.)

types of cell, designated A, B and D (Lane 1907; Bensley 1911; Bloom 1931; Kito & Hosoda 1977). Immunofluorescence microscopy and immuno-electron microscopy (Heitz et al 1976; Baetens et al 1977) have confirmed the identity of their secretory products and revealed other types of endocrine cell. Their general organization is depicted in **12.137**.

The most numerous cells, types A (alpha) and B (beta), respectively secrete glucagon (Baum et al 1962) and insulin (Lacey & Davies 1957). Though interspecific variation exists (Findlay & Ashcroft 1975), human A cells tend to be peripheral in islets and B cells more central (Orci 1976). Cytoplasmic storage granules of A cells are fixed by alcohol, are generally smaller than those of B cells, stain brilliant orange or red with Orange G and Mallory-Azan, and are aldehyde-fuchsin negative; in B cells they are alcohol-soluble and aldehyde-fuchsin positive. A third type, the D cell, discovered in human islets by Bloom (1931), contains somatostatin or a similar peptide (Orci et al 1975). Human D cells are peripherally placed within the islets, like A cells. Orci and Unger (1975) suggested that islets may have two functional regions: a medulla mainly of B cells (where insulin is secreted at a constant rate in response, e.g., to the presence of glucose in the intercellular fluid) and a mixed cortex of A, B and D cells, rich in neurovascular elements (where secretory activity responds rapidly to various environmental changes). In the cortex somatostatin released by D cells may inhibit secretory activity in adjacent A or B cells (Orci 1976). In many mammals, including humans, D cells more often contact A cells than B, suggesting that pancreatic somatostatin may chiefly inhibit glucagon release. Organ culture studies by Barden et al (1977) corroborate this; when anti-somatostatin serum was incubated with rat islets, glucagon release increased tenfold with no significant change in the release of insulin. How somatostatin inhibits the release of glucagon and possibly insulin is not clear; it may act intracellularly, passing through gap junctions from adjacent cells (Gerich & Lorenzi 1978). Another suggested hormonal modifier of islet activity is gastric inhibitory peptide, which appears to potentiate the insulin secretory response to glucose (Dupré et al 1973). The autonomic 'neurohormones', acetylcholine (ACh) and noradrenalin, also affect secretion, ACh augmenting insulin and glucagon release, noradrenalin inhibiting glucose-induced insulin release; they may also affect somatostatin and pancreatic polypeptide (PP) secretion. The roles of the circulating noradrenalin and adrenalin or of neurogenous noradrenalin acting locally on islet cell secretion remain obscure.

Peptide-secreting cells, with smaller granules than those in A, B and D cells, occur in human pancreas, in at least two forms: one contains PP; another has an ultrastructure like that of D_1 cells of the gastric mucosa (p. 1760). Pancreatic 'D_1' cells differ from PP cells in their granules; those of the former do not react with antibovine PP serum, those of the latter do (Baetens et al 1977). Although the product of gastro-enteric D_1 cells is uncertain, it may be related to vasoactive intestinal polypeptide (VIP) (Buffa et al 1977); the product of pancreatic 'D_1' cells is still uncertain.

'D_1' and PP cells are not restricted to islets, being also scattered throughout the predominantly exocrine tissue.

Islet vessels and nerves

Pancreatic vessels. Arteries are rami of the splenic and pancreaticoduodenal arteries (pp. 1551, 1553).

Venous drainage is into the portal, splenic and superior mesenteric veins.

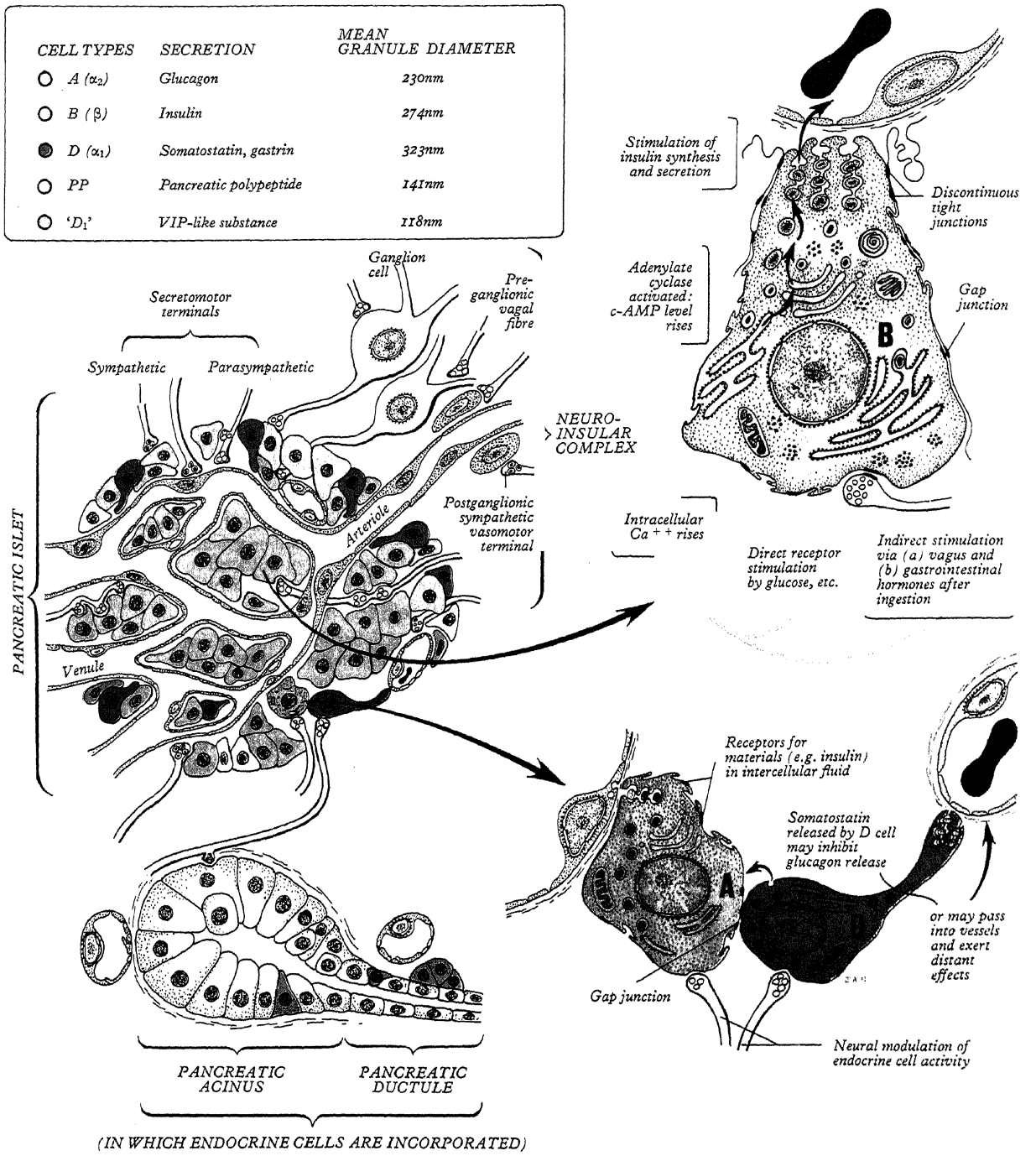
Lymph drainage is described elsewhere (p. 1619). Larger blood and lymph vessels travel with the exocrine ducts and nerves in the interlobular connective tissue, supplying lobular branches. Bunnag et al (1963) have shown that in mice one to three afferent arterioles arise from arterial rami to supply each islet, before which they may supply the acini. In each islet they feed a capillary network almost as dense as in a renal glomerulus; the network is drained by one to six venules which join to enter an intralobular vein. McCuskey and Chapman (1969) reported an intermittent flow in islet capillaries, local interruption being due to luminal bulging of the endothelial cells. The capillaries are fenestrated.

Pancreatic nerve supply. This comes from the coeliac plexus and enters along with the arteries of supply. Little is known of the afferent nerves; the efferents consist of sympathetic postganglionic fibres from the coeliac ganglion and parasympathetic preganglionic from the right vagus. The fibres, mainly nonmyelinated (Benscome 1959), are vasomotor (sympathetic) and parenchymal (sympathetic and parasympathetic) in their distribution. Fine branches ramify among the cells, from peri-insular plexuses (Findlay & Ashcroft 1975). Fibres frequently synapse with acinar cells before innervating the islets, suggesting a close linkage between neural control of exocrine and endocrine components. Many fibres enter the islets with the arterioles (Coupland 1958).

Parasympathetic ganglia lie in the inter- and intralobular connective tissue, and in the latter case are frequently associated with insular cells, forming *neuro-insular complexes*, first described by van Campenhout (1925) as 'complexes sympathico-insulaires', revised to 'complexes neuro-insulaires' by Simard (1937). They were classified by Fujita (1959) in two groups: one of neurons and insular cells (**12.137**), one of nerve fibres and insular cells, the latter being described in detail by Kobayashi and Fujita (1969). Both A and B cells are involved in the neuro-insular complexes.

Three types of nerve terminal are noted in islets (Smith & Porte 1976): cholinergic (with 30–50 nm diameter agranular vesicles), adrenergic (with 30–50 nm dense-cored vesicles), and a third, uncharacterized, type (with 60–200 nm dense-cored vesicles).

No selective link with any one type of insular cell has been found; sometimes more than one type of terminal contacts a single cell (Esterhuizen et al 1968). Some of the chemical synapses between



12.137 Diagram of the histology, ultrastructure and mode of operation of the endocrine pancreas (VIP = vaso-active intestinal polypeptide).

axon terminal and islet cell show narrow areas in the synaptic clefts suggesting an electrical synapse or gap junction (Orci et al 1973); such junctions also occur between islet cells (Orci 1974) and electrical coupling of nerve supply to a functional network of islet cells has been mooted. Some terminals appear remote from the surfaces of islet cells (Kobayashi & Fujita 1969); neuro-transmitters released from them could diffuse through intercellular spaces to affect numerous islet cells.

CLINICAL ANATOMY OF THE PANCREAS

True pancreatic cysts are relatively uncommon. A pseudocyst of the pancreas results from effusion of fluid into the lesser sac as a result of acute pancreatitis or pancreatic trauma. The resultant collection pushes forward between the stomach and transverse colon, becoming palpable in the upper abdomen as a median tumour; the tumour is fixed, and does not move even during respiration. Carcinoma of the pancreas usually affects the head, speedily involving the bile duct, leading to jaundice; or it may press on the portal vein, causing ascites, or obstruct the pylorus. Rarely the ventral pancreatic bud fails to rotate around the duodenum. This results in a ring of pancreatic tissue encircling (and obstructing) the second part of the duodenum (*annular pancreas*). The ventral and dorsal pancreatic ducts may fail to fuse or fuse incompletely. The accessory duct remains as the main duct, draining the tail, body and most of the head. This inadequate drainage may predispose to acute or chronic

pancreatitis. If the bile duct is embedded in the pancreatic head (p. 1809), chronic pancreatitis may obstruct it and produce jaundice. Accessory nodules of pancreatic tissue may exist in the wall of the duodenum (most commonly), jejunum, ileum or ileal diverticulum (p. 1763). They may be associated with duodenal diverticula, as small protrusions of the whole wall or only of the mucosa and submucosa, usually adjacent to the pancreas and the opening of the bile duct.

Pancreatic transplantation is indicated for the treatment of insulin-dependent diabetics who suffer end-stage renal failure due to diabetic microangiopathy; in these cases a kidney is transplanted into the same recipient, usually from the same cadaveric donor. A pancreas may also be transplanted alone in an unstable diabetic in whom renal or other end-organ failu may be anticipated in the near futu The major technical challenge has been to develop a method of draining the exocrine secretions and to prevent a pancreatic fistula. To achieve these ends, a roux-en-y loop of jejunum has been used in the past (Groth & Tyden 1988), but the technique of pancreaticocystostomy is now much more popular (Sollinger et al 1984). The pancreas is always transplanted into the pelvis, either within or outside the peritoneal cavity. In this position, the pancreas can be drained into the bladder or into a small bowel loop, either using a duodenal conduit (**12.**138A), or by anastomosing the cut surfaces of the pancreas to the fundus of the bladder (**12.**139B). The bladder anastomosis offers the technical advantage of being an easier operation, and the function of the gland may be measured by regular measurement of urinary amylase. In immunosuppressed diabetics, where healing is impaired, pancreaticocystostomy seems the safest and

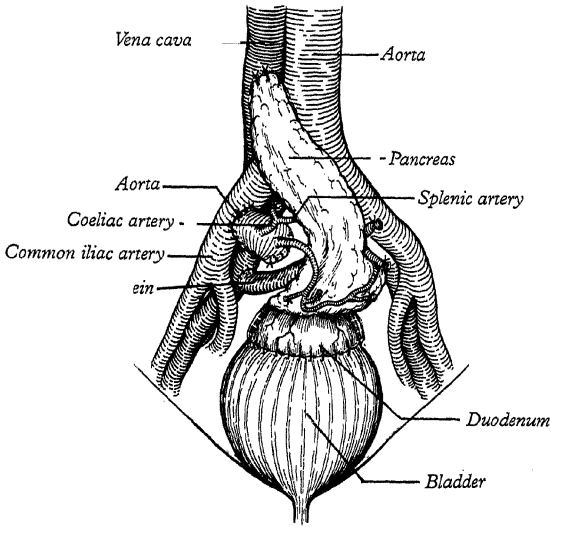
OPERATION OF CADAVERIC PANCREATECTOMY

Following the diagnosis of brain death, the pancreas is dissected free of the transverse mesocolon, and the attachments to the greater curvature of the stomach, including the short gastric vessels, are divided. The splenic vessels are tied at the pancreatic tail and the spleen removed, and the splenic and coeliac arteries, including the superior pancreaticoduodenal artery, are prepared for anastomosis to the recipient artery. If the whole organ is to be transplanted, the duodenum is divided, and the superior mesenteric trunk and inferior pancreaticoduodenal artery are preserved. Since the liver will also frequently be taken for plantation (p. 1808), perfused through the aorta with a cooled preservation solution and excised. A patch of aorta bearing the superior mesenteric and coeliac arteries may be removed, together with a length of portal vein for anastomosis to vessels. 'Jump graft' using sectio

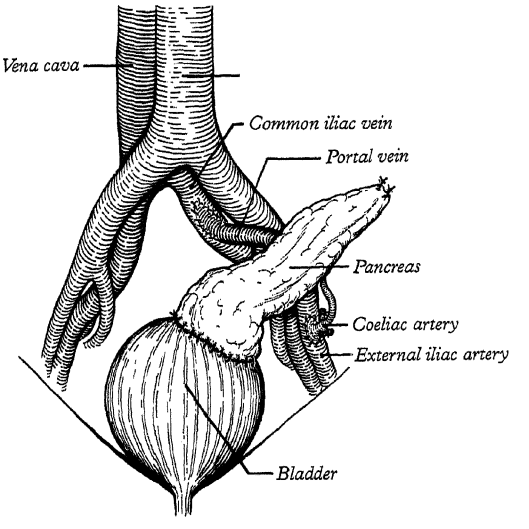
tensi
ent's

RECIPIENT OPERATION

The coeliac and the superior mesenteric arteries are anastomosed to the external iliac artery, and the portal vein to the external iliac vein using a jump graft if necessary. Angulation must be avoided at this anastomosis to avoid a high risk of postoperative thrombosis. The cut pancreatic surface, or the duodenal conduit, are anastomosed to the vault of the bladder.



12.138A Pancreatico-cystostomy with duodenal conduit.

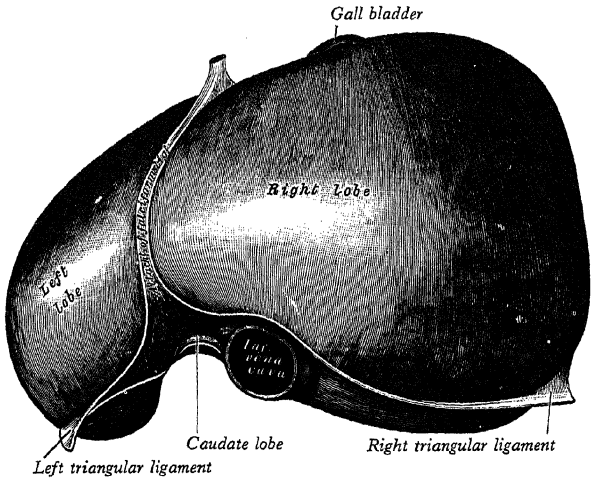


12.138B Pancreatico-cystostomy with the cut surface of the pancreas anastomosed to the fundus of the bladder.

LIVER

INTRODUCTION

The liver is the most massive of the viscera, occupying a substantial portion of the abdominal cavity. It is essential to life, since it carries out a multiplicity of metabolic activities necessary for homeostasis, alimentation and defence. It is composed largely of epithelial cells (hepatocytes) where most of these biochemical operations occur, bathed by blood derived from the hepatic porta veins and hepatic arteries, and draining into the inferior vena cava through the hepatic veins. There is continuous chemical exchange between the



12.139 The superior, anterior and right lateral surfaces of the liver.

hepatocytes and the blood as the cells of the liver elaborate various macromolecules, secreting them either into the blood (e.g. most plasma proteins), or into an extensive system of minute canals which converge on the hepatic duct and thence the gallbladder and bile duct to assist digestion and eliminate the products of haemoglobin breakdown (bile salts and bile pigments, respectively). The hepatocytes are also important in removal and breakdown of toxic, or potentially toxid materials from the blood, for regulation of blood glucose and lipids (stored as glycogen and proteolipid, respectively), storage of certain vitamins, iron, and other substances, breakdown or modification of aminoacids, and a plethora of other biochemical reactions which are predominantly exothermic and therefore provide a substantial part of the body's thermal energy, especially at rest. In addition to these properties, the liver is populated by phagocytic macropohages scattered along the walls of its extensive vascular network; these form part of the mononuclear phagocyte system of the body and are important in the removal of particulates from the bloodstream. Finally, in fetal life the liver is an important site of haemopoiesis. These diverse aspects of liver function are considered further on pp. 1802–1806 with liver microstructure.

EXTERNAL FEATURES (12.139–143)

The liver (hepar) lies in the upper right part of the abdominal cavity, occupying most of the right hypochondrium and epigastrium and extending into the left hypochondrium as far as the left lateral line (Rouiller 1964). In males it generally weighs 1.4–1.8 kg, and in females 1.2–1.4 kg, with a range of 1.0–2.5 kg. It is somewhat cuneiform, is reddish brown in colour in the fresh state and, though firm and pliant, is easily lacerated. Wounds cannot be tightly sutured and bleeding may be severe, due to the organ's great vascularity. Despite its weight, it is widely believed that, like various other viscera, its position is not maintained by peritoneal (p. 1798) or fibrous attachments, but mainly by intra-abdominal pressure due to tonus in the abdominal muscles. The continuity of hepatic veins with the inferior vena cava may provide some support. However, such dogma should be viewed with caution. Without systematic studies of intra-abdominal pressure gradients and their variations with posture, respiration, gastrointestinal dilatation and so forth, and studies of the statics and dynamics of the peritoneal folds, connective tissues, adjacent viscera and vascular pedicles, any theories as to the other mechanisms maintaining the position of the liver (or any other abdominal organ) remain highly speculative.

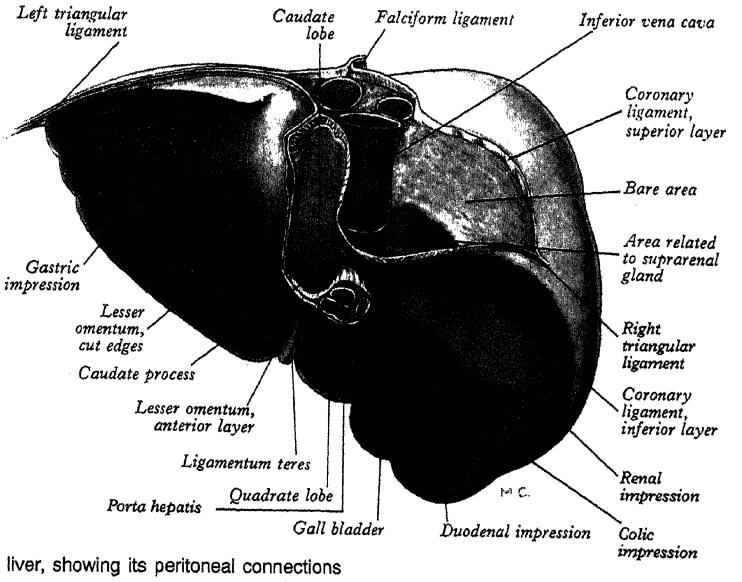
The liver is a wedge-shaped, rather rounded organ, its narrow end pointing left, and its anterior edge directed downwards. It is convex in front, to the right, above and behind, where it abuts the curved surfaces of the anterior body wall and diaphragm, and it is somewhat concave inferiorly where it is moulded to the shapes of the adjacent viscera. The liver is attached in front to the body wall by the *falciform ligament*, and above and behind to the diaphragm by the *coronary ligament* with its lateral limits, the *right* and *left triangular ligaments* (forming reflexions of the peritoneum from the liver surface on to the diaphragm). Below, it is attached to the stomach and first part of the duodenum by the lesser omentum, along the right (free border) of which the hepatic arteries, hepatic portal vein, lymphatics, nerves and hepatic ducts enter or leave the liver at the *porta hepatis* (the door to the liver), an area also termed the *hilus*. The gallbladder adheres to the anterior part of the liver's inferior surface.

The inferior surface is marked near the midline by a sharp fissure which anteriorly receives the *ligamentum teres* (the obliterated fetal left umbilical vein) from the free edge of the falciform ligament, and posteriorly contains the *ligamentum venosum*, another obliterated relic of the fetal circulation. The lesser omentum is reflected on to the liver along the posterior half of this fissure.

Posteriorly, the liver is deeply grooved where it partially surrounds the inferior vena cava (the caval groove) which receives the large hepatic veins in this region.

Lobes

Although much of the surface is smoothly continuous, the liver is customarily apportioned by anatomists into a larger *right* and a much smaller *left lobe* according to some surface markings and



12.140 Posterior aspect of the liver, showing its peritoneal connections divided close to its surfaces.

peritoneal attachments (see p. 1798), namely the line of attachment of the falciform ligament anteriorly, and the fissure for the ligamentum teres and ligamentum venosum on the liver's inferior surface. To the right of this groove are two prominences, the *quadrate lobe* in front, and the *caudate lobe* behind, separated from each other by the porta hepatis. The gallbladder lies (usually) in a shallow fossa to the right of the quadrate lobe.

It is important to note that while this brief description of lobation is didactically convenient, it does not reflect the liver's internal vascular or biliary subdivisions, which are of considerable surgical importance. A fuller consideration of this topic is given below.

Surfaces (12.139–141)

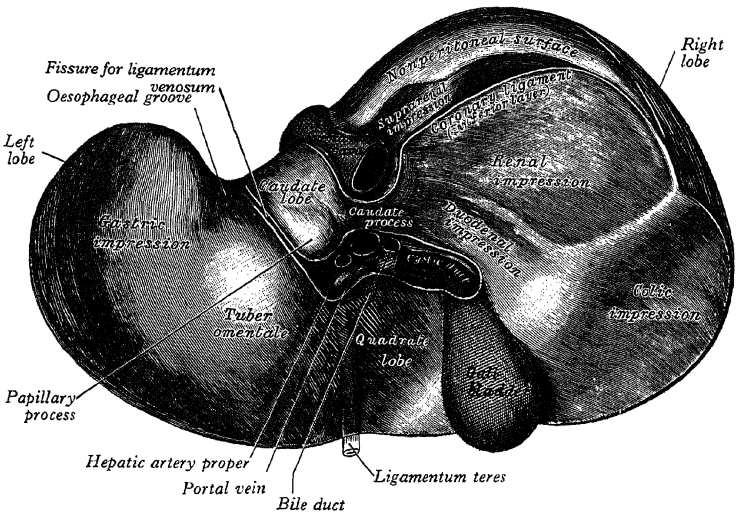
The liver is described as having *superior, anterior, right, posterior* and *inferior surfaces*, and a distinct *inferior border*. The superior, anterior and right surfaces are continuous at rounded 'borders', but the sharp inferior border (12.140) separates the right and anterior surfaces from the inferior surface. This border is rounded between the right lateral and inferior surfaces, but becomes thin and angular at the lower limit of the anterior surface and is notched along this edge by the ligamentum teres, just to the right of the midline. Lateral to the fundus of the gallbladder, which often corresponds to a second notch 4–5 cm to the right of the midline, the inferior border largely follows the costal margin. Left of the fundus it ascends less obliquely than the right costal margin, crossing the infrasternal angle to pass behind the left costal margin near the tip of the eighth costal cartilage. It then ascends sharply to merge with the thin margin of the left lobe. At the infrasternal angle the inferior border adjoins the anterior abdominal wall and is accessible to examination by percussion, but is not usually palpable; in the midline the inferior border of the liver is near the transpyloric plane, about a hand's breadth below the xiphisternal joint (12.117). In women and children the border often projects a little below the right costal margin. The hepatic surfaces are described in greater detail on p. 1800.

HEPATIC LOBATION (12.142, 143)

As already noted (see above), the customary subdivision of the liver into right and left lobes does not really describe the internal organization of this organ, which is generated by developmental processes only hinted at on the mature liver's surface. With recent developments in surgery, especially liver transplantation, and the introduction of powerful imaging methods which can be used before and during operations, it has become vital to understand the vascular and biliary territories which can be isolated as units for partial hepatectomy and other local surgical interventions (see below; see also e.g. Bismuth, Aldridge & Kunstlinger 1991).

These patterns have been established over the last century by a series of classical studies on the liver's vascular and biliary duct branching patterns, by dissection and injection methods, especially the use of corrosion casts. Cantlie (1898) first established the division of the liver into right and left halves (which do not correspond to those of traditional anatomists, see above) according to the distribution of right and left hepatic arteries, (sometimes referred to now as right and left livers). Later work by Hjortsjö with corrosion casts (Hjortsjö 1948, 1951, 1956) definitively established the major vascular territories of the arterial and hepatic venous supply and drainage, and of the biliary tree; he emphasized that primary anatomical and functional lobation are better defined as the territories of the right and left hepatic ducts and showed that there is only minor overlap between them. These studies were combined with surgical data in the classic book by Couinaud (1953) which is now regarded by many as a definitive descriptive foundation for surgical approaches to the liver.

Other workers have confirmed Hjortsjö's classification and have made further subdivisions of lobes into segments, as described below (e.g. Healey & Schroy 1953; Goldsmith & Woodburne 1957; Stucke 1959), by corrosion cast techniques, dissection and radiology. In such investigations, particularly those involving examination of casts of ducts or vessels, so-called 'fissures' are visible (12.141) between the territories of the right and left branches, and less clearly between lobar subdivisions (segments). These fissures, even in the main interlobar zone, do not produce reliable surface indications of use in lobectomy.



12.141 The inferior surface of the liver.

Right lobe

Much the greater in volume, it contributes to all surfaces, as described later, including the entire costal aspect. Its arbitrarily described surfaces (anterior, superior, inferior and posterior) all pass uninterruptedly on to the *left lobe*, except where shallow grooves partially demarcate the quadrate and caudate 'lobes', really parts of the left lobe, as already mentioned.

Quadrate lobe

Visible on the inferior surface, it appears somewhat rectangular and is bounded in front by the inferior border, on the left by the fissure for ligamentum teres, behind by the porta hepatis and on the right by the fossa for the gallbladder.

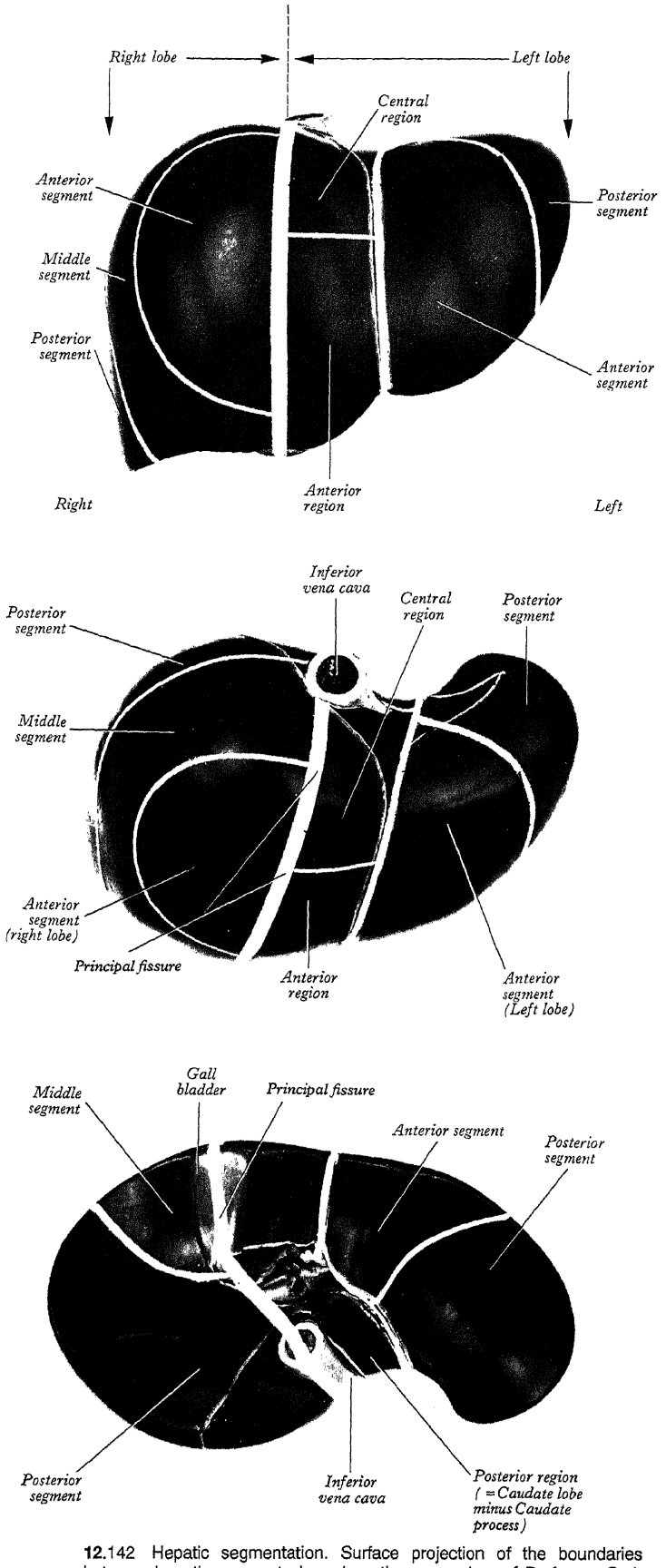
Caudate lobe

This is visible on the posterior surface, bounded on the left by the fissure for the ligamentum venosum, below by the porta hepatis and on the right by the groove for the inferior vena cava. Above, it continues into the superior surface on the right of the upper end of the fissure for the ligamentum venosum. Below and to the right, it is connected to the right lobe by a narrow *caudate process*, which is immediately behind the porta hepatis and above the epiploic foramen. Below and to the left, the caudate lobe has a small rounded *papillary process*. Due to the depth of the fissure for the ligamentum venosum, the caudate lobe has an anterior surface, which forms the posterior wall of the fissure and is in contact with the lesser omentum (hepatic part).

HEPATIC SEGMENTATION

As in other organs with a group of hilar structures (e.g. the lungs, spleen, kidneys), the branching patterns of blood supply and biliary drainage in the liver create a system of lobes and further subdivisions (sectors or segments). This reflects the early development of the liver when the branching patterns of epithelial ducts, their related arteries and portal vein rami, and also the venous drainage to the inferior vena cava are established. Of course, what is designated as a segment must be rather arbitrary, depending on what level of branching is chosen as its basis for separation from other segments. However such schemes have a practical value in that the territories of the larger vessels do not overlap extensively or for many anastomoses, and this can be exploited during partial hepatectomy (provided enough imaging information is available for a particular patient, as considerable variation can occur).

The hepatic artery, portal vein and common bile duct divide and subdivide with a common pattern, as implied in the classic observations of Glisson (1654) and confirmed by subsequent workers. No evidence of significant intrahepatic anastomosis in these



12.142 Hepatic segmentation. Surface projection of the boundaries between hepatic segments based on the researches of Professor Carl-Herman Hjortsö, University of Lund, Sweden. See text for comment and references. Top: anterior view; middle: anterosuperior view; bottom: inferior visceral views.

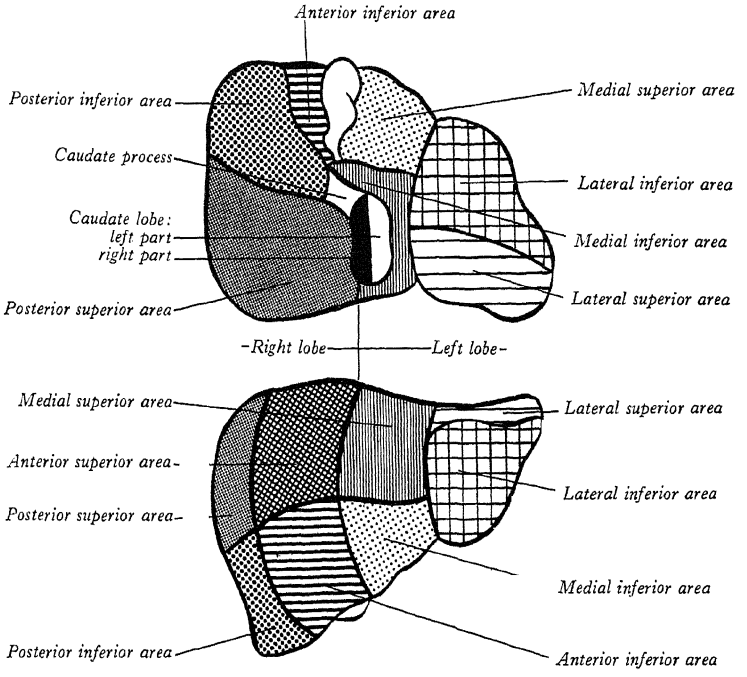
dendriform systems has been recorded. For example, despite variation in origin (and occurrence of accessory vessels), the hepatic arterial system consists of end-arteries (Michels 1966), a feature typical in any organ developed from a single vascularized blastema of dichotomizing potential. The implications of this pattern were not followed up until the late nineteenth century, apart from the recognition of right and left hepatic lobes (see McIndoe & Counsellor 1927; Hjortsjö 1948 for earlier literature). Division into two lobes, based on the primary divisions of the triadic system (hepatic arteries, portal veins and biliary tree) rather than on surface features, is generally accepted but confusing descriptions persist in many texts. Inevitably, further divisions have been suggested, if only in the interests of effective partial hepatectomy. The pioneer in this field was Hjortsö (1948, 1951, 1956, 1975), who was the first to propose a complete segmental model (**12.142**), based on dissections, injections and radiography, particularly applied to the biliary ducts and portal vein. Many have subsequently modified his scheme of segmentation, subdividing some segments, redefining and renaming others (Elias & Petty 1952; Healey & Schroy 1953; Couinaud 1954; Goldsmith & Woodburne 1957; Bilbey & Rappaport 1960). The main extension of Hjortsö's scheme is the division of his segments into superior and inferior parts, chiefly by Healey and Schroy 1953 (**12.143**) and Couinaud 1954. Apart from this and minor differences in delineating the major segments, there is general consensus on the division of the right lobe into approximately 'anterior', intermediate and 'posterior' segments; and the left into lateral and medial parts.

Most reports have been based on injections and casts, principally upon corrosion casts of one or more of the components of the triad's ramifications. In such casts is an easily discernible (**12.144**) sagittal zone between the lobes, the *fissura principalis*, picturesquely described by Hjortsö (1956) as lying in the plane of the left tympanic membrane. All other 'fissures' described (with some variation) by different workers are intersegmental. The term *'spatium'* was suggested for 'fissure', and Hjortsö recognized several of these (**12.142**). Such 'spaces' in corrosion casts are due to the absence of all but the smallest rami of the portal triad, usually too fragile to preserve. These demarcations do **not** correspond to substantial zones of connective tissue, which might provide superficial or internal indications for purposes of subtotal resection (cf. bronchopulmonary segments). Surface projections of segmental fissures are shown in **12.143**, according to Hjortsö (1948) and Healey and Schroy (1953), the chief difference being that the latters' scheme shows superior and inferior regions in each major segment (as also recognized by Elias & Petty 1952; Couinaud 1954; and Platzer & Maurer 1966). More recently Gupta et al (1977) have put forward a similar scheme (9 segments); in 1981 further observations by Gupta et al on hepatovenous segmentation in the human liver were published in which they recognized five segments: left, middle, right, paracaval and caudate. To equate the segments described, with their differing names and delimitations, by all the investigators quoted would not improve the reliability of this information in practical application. As Gupta et al (1978) stated, the segmental pattern is in itself variable; of 41 corrosion casts more than half showed marked differences in the volume of one segment or another, as also noted by others. Although most regard segments as functionally independent and uncomplicated by, e.g. intrahepatic arterial anastomosis, occasionally this has been noted.

Surgical opinion is divided upon the usefulness of such patterns in hepatic resections. Dawson (1974) and others consider resection of less than a lobe to be hazardous; others, such as Ryncki (1974), have recorded successful segmental resections. Individual variation requires portal venography and cholangiography to define segmental patterns before operation, wherever feasible. It should be noted that the disposition of the *hepatic veins* and their tributaries is not a reliable guide; these veins, also studied by corrosion casts (Goldsmith & Woodburne 1957), do not follow the pattern of the hepatic triads; they drain parts of adjoining segments. It is therefore difficult to plan a resection plane which is optimal in respect of both triadic structures and hepatic veins.

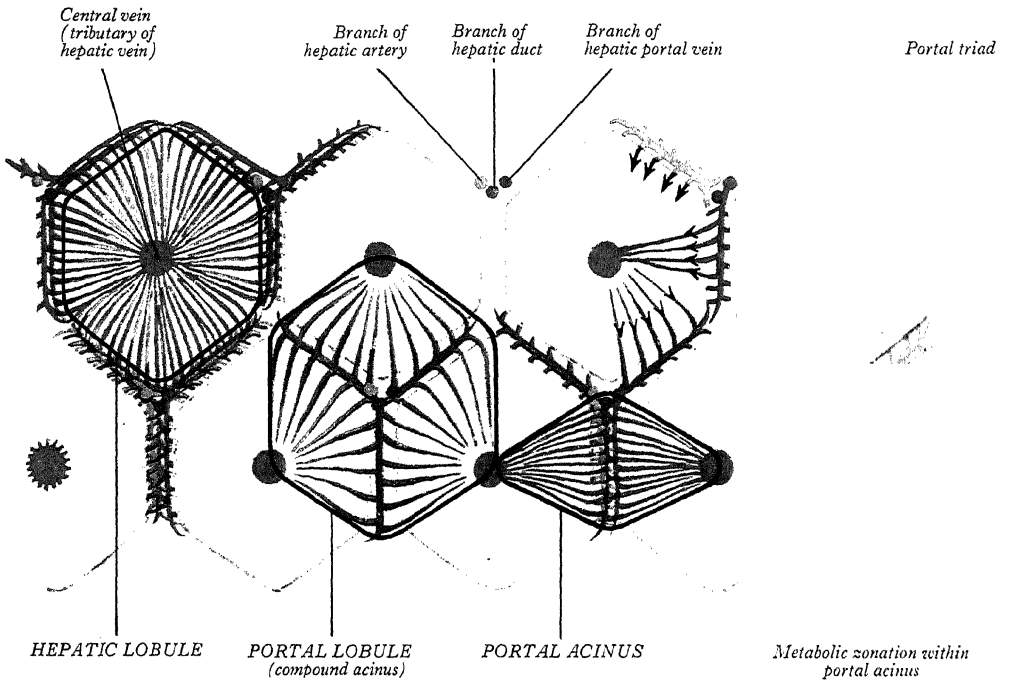
PERITONEAL CONNECTIONS OF THE LIVER

Except for a triangular area on its posterior surface (the 'bare area'), the liver is almost completely covered by peritoneum, which connects



12.143 The segmentation of the liver, based upon the principal divisions of the hepatic artery and accompanying hepatic ducts. The upper drawing is of the visceral surface of the liver, the lower drawing is of the diaphragmatic surface. See text for further description.

12.144 A resin corrosion cast of the blood vessels and duct systems of the liver of a woman: bile duct, cystic duct, gallbladder and their tributaries (yellow); the hepatic artery and its branches (red); the portal vein and its tributaries (light blue); the inferior vena cava, hepatic veins and their tributaries (dark blue). The photograph is of the visceral surface of the organ and was taken before the finer blood vessels and ducts were removed by trimming. The posterior aspect is above. Prepared by D H Tompsett of the Royal College of Surgeons of England.



12.145 Diagram of the histological organization of the liver, showing the principal types of subdivisions which have been proposed. For purposes of clarity, the territories of the classic hepatic lobules are shown as regular hexagons, unlike their real appearance which is highly variable (see text).

it to the stomach, duodenum, diaphragm and anterior abdominal wall by several folds, their lines of attachment, of course, being devoid of peritoneum. These folds include the falciform ligament, right and left triangular and coronary ligaments and the lesser omentum.

Falciform ligament (12.71, 72, 139)

A crescentic fold, it consists of two applied layers of peritoneum, connecting the liver to the diaphragm and the supra-umbilical part of the anterior abdominal wall. Its convex base is fixed to the inferior diaphragmatic surface and to the posterior surface of the anterior abdominal wall, down to the umbilicus; as it ascends from this it inclines slightly right. It is attached to the notch for the ligamentum teres on the inferior hepatic border and to the anterior and superior hepatic surfaces. Its concave free edge, from the umbilicus to the notch for the ligamentum teres, contains the latter structure and the small para-umbilical veins, and is anterior to the pyloric region of the stomach. At its diaphragmatic end its layers separate to expose a triangular area on the superior hepatic surface devoid of peritoneum. The left layer continues into the anterior layer of the left triangular ligament, the right into the upper layer of the coronary ligament.

Coronary ligament (12.76, 140)

This name is given to the reflexion of peritoneum from the diaphragm to the superior and posterior surfaces of the right lobe of the liver, forming the perimeter of the approximately triangular but rather variable 'bare area' of the liver, i.e. that part of its surface which is apposed to the diaphragm without intervening peritoneum. The coronary ligament has upper and lower margins or layers, united laterally at angular extensions, the left and right triangular ligaments. Followed from left to right (see **12.76**), the upper layer departs from the right side of the falciform ligament (with which it is continuous), skirts anteriorly the upper end of the groove for the inferior vena cava, then descends obliquely down and to the right on the back of the liver to the anterior (upper) leaflet of the right triangular ligament. The lower layer then begins with the posterior (lower) leaflet of the right triangular ligament, then can be followed to the left almost horizontally along the lower limit of the right lobe's posterior surface. Here the coronary ligament is sometimes reflected on to the upper part of the right kidney's anterior surface (so forming the hepatorenal ligament). At its left extremity, the lower layer of the coronary ligament passes in front of the lower end of the groove for the inferior vena cava, and becomes continuous with the right margin of the lesser omentum where it is reflected from the right margin of the caudate lobe. Above, this curves to the left to become the inferior (posterior) layer of the left triangular ligament, the term 'ligament' for this complex line of peritoneal reflexion indicates a supportive function, aiding the fibrous attachment of the bare area in suspending the liver from the diaphragm and posterior body wall. Its precise boundary reflects the development of the liver in the ventral mesogastrium and its later attachment to adjacent structures (see p. 342).

Left triangular ligament (12.140)

It ascends back from the superior surface of the left lobe to the diaphragm. Its closely applied layers become fused at the left edge of the ligament. To the right the anterior layer merges with the left layer of the falciform ligament, the posterior with the anterior layer of the lesser omentum at the upper end of the fissure for the ligamentum venosum. The left triangular ligament lies in front of the abdominal part of the oesophagus, the upper end of the lesser omentum and part of the fundus of the stomach. It varies much and may contain large blood vessels (Outrequin et al 1967).

Right triangular ligament (12.140)

This is a short V-shaped fold connecting the lateral and posterior aspects of the right lobe to the diaphragm. At its right margin its two layers are continuous. The ligament is really the right extremity of the coronary ligament.

Lesser omentum

It has been described (p. 1741); it is attached along the line of the fissure for the ligamentum venosum, at the upper end of which its anterior layer merges with the posterior layer of the left triangular ligament and its posterior layer with the line of reflexion of the peritoneum from the upper end of the right caudate lobe and so, indirectly, with the lower coronary layer (**12.140**).

Superior surface

The superior surface (**12.139**) includes parts of the right and left lobes. It fits closely under the diaphragm, separated from it by

peritoneum except for a small triangular area where the two layers of the falciform ligament diverge. Right and left it is convex, but centrally it presents a shallow *cardiac impression* corresponding with the position of the heart above the diaphragm. It is related to the right diaphragmatic pleura and base of the right lung, to the pericardium and ventricular part of the heart and to part of the left diaphragmatic pleura and base of the left lung. It should be noted that the superior surface curves directly into the so-called anterior surface and the peritonealized part of the posterior surface of the right lobe. No definable border separates superior, anterior, right lateral and right posterior *aspects* of the liver and it would be more appropriate to group these as the *diaphragmatic surface*, mostly separated from the *visceral surface* by a narrow edge or border.

Anterior surface

The anterior surface, which is triangular and convex, is covered by peritoneum except at the attachment of the falciform ligament. Much of it is in contact with the diaphragm, which separates it on the right from the pleura and sixth to tenth ribs and cartilages, and on the left from the seventh and eighth costal cartilages. The thin margins of the base of the lungs are thus quite close to the upper part of this surface, more extensively so on the right. The median area of the anterior hepatic surface lies behind the xiphoid process and the anterior abdominal wall in the infra-costal angle (**12**.117).

The hepatic profile is projected to the surface of the body as follows (**12**.117): its upper limit corresponds to a line through the xiphisternal joint, ascending to a point below the right nipple (fourth intercostal space) and to the left to a point inferomedial to the left nipple; its right border corresponds to a curved line, convex to the right, running from the right end of the upper border to a point 1 cm below the costal margin at the tip of the tenth costal cartilage; its lower limit is the line completing this triangle (**12**.117), crossing the midline at the transpyloric plane (slightly concave near the right linea semilunaris).

Right surface

The right surface, covered by peritoneum, adjoins the right dome of the diaphragm which separates it from the right lung and pleura and the seventh to eleventh ribs. Above its upper third, both lung and pleura are inserted between the diaphragm and ribs; over its middle third only the costodiaphragmatic pleura is interposed; over its lower third the diaphragm and thoracic wall are in contact.

Posterior surface

The posterior surface is convex and wide on the right but narrow on the left, with a deep median concavity corresponding to the forward convexity of the vertebral column (**12**.140, 141). Much of this surface is devoid of peritoneum, being attached to the diaphragm by loose connective tissue, forming the so-called 'bare area', triangular in shape and limited above and below by the layers of the coronary ligament. The base of the posterior hepatic surface to the left is the caval groove; its apex, directed down and right, corresponds to the right triangular ligament. The *groove for the inferior vena cava* (caval groove), which is deep and occasionally a tunnel, lies at the posterior surface and is bare of peritoneum and adapted to the upper part of the vessel it contains; its floor is pierced by the hepatic veins (p. 1602). Infero-anteriorly the caudate process separates it from the porta hepatis. Lateral to its lower end the 'bare area' adjoins the upper pole of the right suprarenal gland. Left of the groove the *caudate lobe* forms the posterior surface in the superior omental recess; the peritoneum on its posterior aspect curves round its left border to its anterior aspect, which is the posterior wall of the fissure for the ligamentum venosum (**12**.141). The caudate lobe projects into the superior omental recess from the right; its posterior surface is related to the diaphragmatic crura (above the aortic opening) and the right inferior phrenic artery, separated by them from the descending thoracic aorta. The *papillary process* often descends in front of the origin of the coeliac artery.

The *fissure for the ligamentum venosum* (**12**.141) separates the posterior aspect of the caudate from the main part of the left lobe. The fissure cuts deeply in front of the caudate lobe and contains the two layers of the lesser omentum. Below, it curves laterally in front of the papillary process to the left end of the porta hepatis. The *ligamentum venosum*, the fibrous remnant of the ductus venosus (p. 1502), is attached below to the left branch of the portal vein's posterior aspect; ascending in the floor of the fissure and passing laterally at the upper end of the caudate lobe it joins the left hepatic vein near its entry into the inferior vena cava, or sometimes the vena cava itself.

The left lobe's posterior aspect has a shallow *oesophageal impression* near the upper end of the fissure for the ligamentum venosum, occupied by the abdominal part of the oesophagus. Left of this the left lobe is related to part of the fundus of the stomach.

Inferior surface (**12**.140, 141)

Facing down, back and to the left, it bears the imprint, when preserved in situ, of the adjacent viscera. It is covered by visceral peritoneum except at the porta hepatis, the fissure for the ligamentum teres and the fossa for the gallbladder. On the left lobe, continuous with the oesophageal groove, is a *gastric impression*. To the right of this the rounded *omental tuberosity*, in the concavity of the lesser curvature, is in contact with the lesser omentum. The *fissure for the ligamentum teres*, of variable depth, ascends backwards from its notch on the inferior hepatic border to the left end of the porta hepatis, meeting the lower end of the fissure for the ligamentum venosum. It is the left boundary of the quadrate lobe and may be, partially or wholly, bridged by a band of liver. In its floor is the *ligamentum teres*, the obliterated vestige of the left umbilical vein (p. 1502). From the umbilicus this ligament ascends in the edge of the falciform ligament to the inferior hepatic border, where it traverses the fissure to join the left branch of the portal vein at the left end of the porta hepatis, opposite the attachment of the ligamentum venosum.

The gastric impression may invade anteriorly the *quadrate lobe*, which is moulded to the pyloric region and the beginning of the duodenum. The posterior part of the quadrate lobe adjoins the right border of the lesser omentum and its contained structures. When the stomach is empty the quadrate lobe is related to the first (superior) part of the duodenum and part of the transverse colon.

The *porta hepatis*, situated between the quadrate lobe in front, and the caudate process behind, is a deep transverse fissure between the upper ends of the fissure for the ligamentum teres and the fossa for the gallbladder. At the porta hepatis the portal vein, hepatic artery and hepatic nervous plexus enter the liver, and the right and left hepatic ducts and some lymph vessels emerge from it. The hepatic ducts are anterior, the portal vein and its branches posterior and the hepatic artery proper with its branches lies intermediate in position.

The *caudate process* connects the inferolateral part of the caudate lobe (left lobe) to the right lobe. It lies behind the porta hepatis, in front of the inferior vena cava, and roofs the epiploic foramen. It is often assigned to the right lobe but lies within the territory of the left hepatic duct, i.e. it forms part of the **left** lobe (see above).

The *fossa for the gallbladder*, forming the right limit of the quadrate lobe, extends from the inferior hepatic border to the right end of the porta hepatis. Usually shallow, it is variably bare of peritoneum. The inferior hepatic surface to the right of the fossa adjoins the colon, kidney and duodenum. A *colic impression* fits the right colic flexure near the inferior border. A *renal impression*, usually well marked, lies behind the colic impression and is separated from the neck and adjoining part of the gallbladder by a duodenal impression; it is related to the upper pole of the right kidney and superomedially to the lower pole of the right suprarenal gland. When the lower coronary layer is reflected from the liver to the right kidney, the renal and suprarenal impressions extend to the lower part of the 'bare area'. The *duodenal impression* is lateral to the neck of the gallbladder and related to the junction of the first (superior) and second (descending) parts of the duodenum.

It is noteworthy that hepatic relations vary with posture and respiration. In the above description the body is assumed to be supine.

Variations

The branches of the portal vein and tributaries of the hepatic veins are more numerous before birth, after which they are reduced by fusion or degeneration. The fetal portal vein joins the umbilical vein in a smooth right-hand curve, maintained after birth, with a sharp angle between the portal trunk and its left branch; the left vascular

lobe may therefore be at a circulatory disadvantage and unable to keep pace in growth with the right. At the left end of the adult left lobe a fibrous band (*fibrous appendix of the liver*) may appear as an atrophied remnant of the more extensive part of the left lobe found in children; it contains atrophied bile ducts, the *hepatic vasa aberrantia*. Similar remnants may occur in the left lobe's edges and near the inferior vena cava. Occasionally the right lobe's lower border, to the right of the gallbladder, projects down as a broad linguiform process (*Riedel's lobe*).

HEPATIC VESSELS

The vessels connected with the liver are the portal vein, hepatic artery proper and hepatic veins. The *portal vein* and *hepatic artery* proper ascend in the lesser omentum to the porta hepatis, where each bifurcates. The *bile duct* and *lymphatic vessels* descend from the porta in the same omentum (the hepatic artery lying anteriorly and to the left, the bile duct anteriorly and right, and the hepatic portal vein posteriorly). All these structures are enveloped in the *perivascular fibrous capsule* (*hepatobiliary capsule of Glisson*), a sheath of loose connective tissue, which also surrounds the vessels as they course through the portal canals in the liver. It is also continuous with the fibrous hepatic capsule.

Hepatic artery and its branches (12.156)

After variable courses in the porta, these divide and subdivide in the liver, their smaller rami being associated with those of the portal vein with which they are distributed. There are no (or very few) anastomoses between their territories; each is an end-artery (Glauser 1953).

Hepatic veins (12.140, 144)

They convey blood from the liver to the inferior vena cava (p. 1602). They have only a thin tunica adventitia, binding them to the walls of their canals within the liver; hence, in sections, they are widely open and solitary, and so easily distinguished from the branches of portal veins, which tend to collapse post-mortem and are always accompanied by an artery and a biliary duct.

Hepatic lymph vessels

These are described on page 1619. Lymph from the liver has an abundant protein content. Obstruction of the hepatic venous drainage increases the flow of lymph in the thoracic duct. The importance of the transdiaphragmatic lymph drainage of the liver into internal mammary and diaphragmatic lymph nodes has been emphasized by Nidden et al, who confirm that lymph reaches the right lymphatic duct, partly via the tracheobronchial lymph nodes.

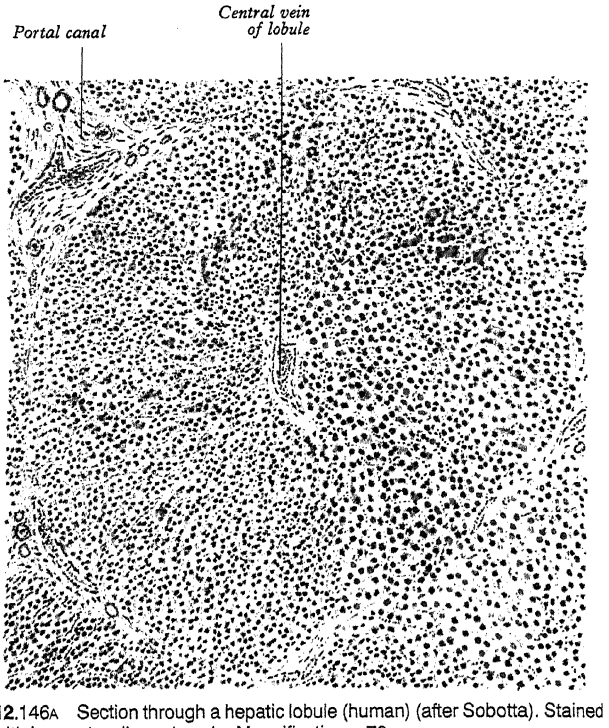
INNERVATION

The hepatic nerves arise from the hepatic plexus (p. 1307) containing sympathetic and parasympathetic (vagal) fibres. They enter at the porta hepatis and largely accompany blood vessels and bile ducts; very few run amongst the liver cells and their terminations are uncertain. Both myelinated and non-myelinated fibres reach the liver from nerves in its various peritoneal folds (Sutherland 1965).

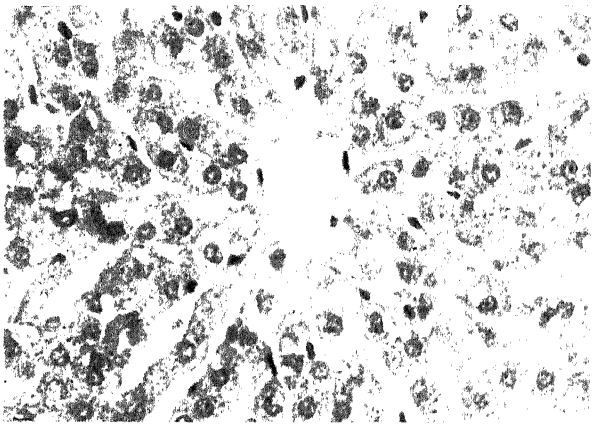
HEPATIC MICROSTRUCTURE (12.145–152)

The liver is essentially an epithelial-mesenchymal outgrowth of the caudal part of the foregut (p. 187), with which it retains its connection by the biliary tree. During development it is penetrated by vascular and connective tissue elements, and defensive cells migrate into its vascular spaces. When fully formed it consists of a complex network of epithelial cells interpenetrated and ensheathed by supportive connective tissue, and permeated by great numbers of blood vessels perfusing the liver with a rich flow of blood from the hepatic portal vein and hepatic arteries. The epithelial cells, *hepatocytes*, carry out the major metabolic activities of this organ, but are assisted by additional classes of cell which possess storage, phagocytic and mechanically supportive functions.

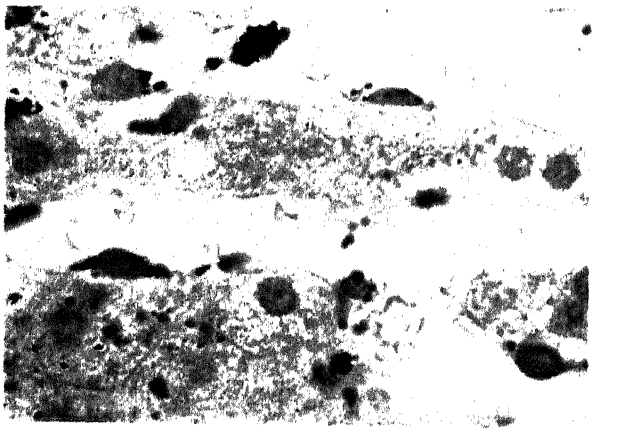
The hepatocytes are arranged in anastomosing plates (*hepatic laminae* or *cords*: see below) lined by endothelium and separated from each other by vascular spaces (*hepatic sinusoids*). Bile secreted



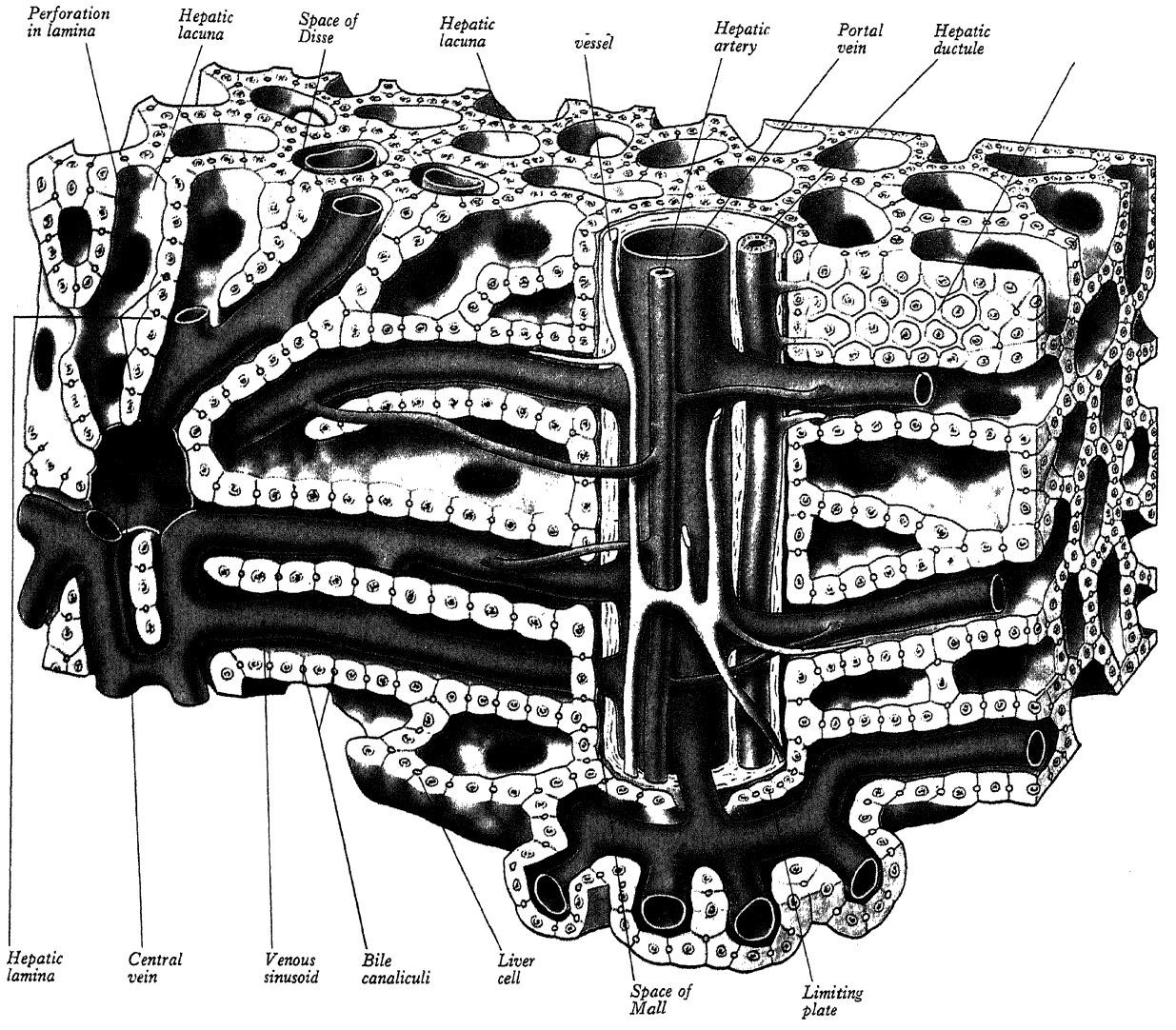
12.146A Section through a hepatic lobule (human) (after Sobotta). Stained with haematoxylin and eosin. Magnification × 70.



12.146B Section through a number of hepatic cords radiating from a central hepatic venule of the rabbit. The hepatocytes appear cuboidal and the Kupffer and endothelial cells, which line the sinusoids, have flattened, densely staining nuclei. Haematoxylin and eosin.



12.146C Section similar to that shown in B, but taken from the liver of a rabbit previously injected intravenously with carbon particles. The Kupffer cell nuclei are outlined with phagocytosed particles which demonstrate the limits of the cell cytoplasm.



12.147 Diagram of hepatic microstructure (after H Elias, Department of Anatomy, Chicago Medical School). Note that in this picture, perisinusoidal endothelial cells and macrophages (Kupffer cells) are not shown.

by the hepatocytes is collected in a network of minute tubes (*canaliculi*) which, in the hepatic cords, are formed by the apposition of corresponding rounded grooves in the lateral walls of the hepatocytes themselves. Bile drains in a direction opposite to the flow of blood through the neighbouring sinusoids, and is collected at the ends of the hepatic cords by epithelium-lined *hepatic ductules* which join others to form the biliary tree. The hepatocytes can therefore be regarded as exocrine cells, secreting bile to the alimentary tract via the hepatic ducts and bile duct; however, they also have another metabolic orientation, that is, towards the blood with which hepatocytes are engaged in a complex series of chemical exchanges.

The surface of the liver facing the peritoneal cavity is lined by typical serosa (the visceral peritoneum); beneath this, and enclosing the whole structure, is a thin (50–100 μm) layer of connective tissue ('Glisson's capsule') from which extensions pass into the liver, branching and rebranching as connective tissue septa and trabeculae. Branches of the hepatic arteries and hepatic veins, together with bile ductules and ducts, run within these connective tissue trabeculae which are termed *portal tracts* (portal canals). The combination of the two types of vessel and a hepatic duct is termed a *portal triad*, a name not strictly accurate because these structures are usually accompanied by one or more lymphatic vessels.

Lobulation of the liver

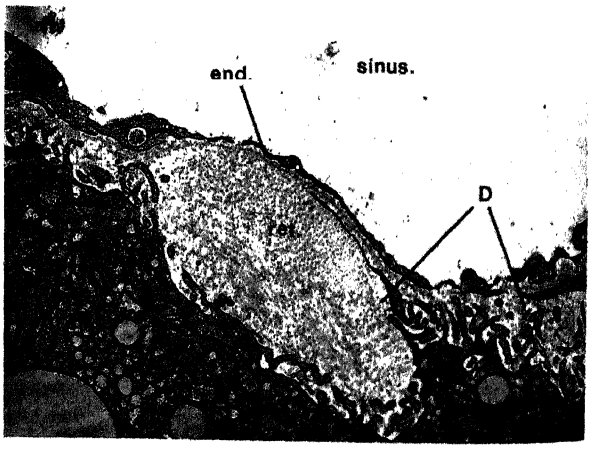
At first sight, the microscopic organization of the liver appears rather chaotic, with (in humans) no obvious arrangement of hepatic cords into discrete groups (**12.146**). However, it is known that specific patterns of cellular degeneration occur in different disease states, indicating the presence of functional units in the normal as well as the pathological liver. Detailed studies with three-dimensional reconstruction and morphometric analysis, combined with observations of clinical and experimental pathology, have provided a picture of what is essentially a highly orderly arrangement of cell clusters, or *lobules*, centred around the smallest afferent vessels and bile ductules of the liver. However, the term 'lobule' has a rather chequered history, and requires some explanation and qualification.

As originally described in the adult pig and some other mammals, the liver is composed largely of prismatic clusters of hepatocytes, each group or *classical lobule* often being hexagonal, about 1 mm in diameter and enclosed in loose connective tissue. Within this unit, hepatic cords are arranged like the spokes of a wheel about a central *terminal hepatic venule* (centrilobular venule, or central vein), a tributary of an hepatic vein. However, in man (and many other mammals) such well-defined classical lobules are not usually present. The three-dimensional reconstructions by Rappaport (1969, 1987) and other studies have substituted the concept of the *portal lobule* centred on a near-terminal branch of an hepatic artery and portal vein, and their related bile ductule. Referring to the situation in the pig liver, this territory corresponds to sectors of at least three 'classic' lobules (**12.145**). Hence, in sections, a portal lobule is a polygonal territory centred on a portal triad, its boundary passing through adjacent central veins. A subunit of this territory, the *portal acinus*

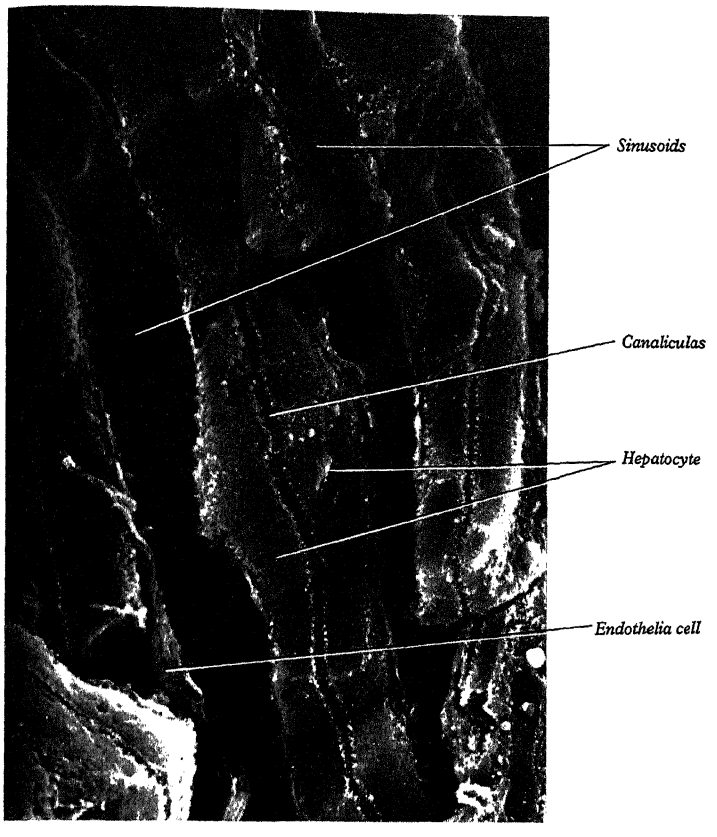
12.148 Schema illustrating the chief cellular features of an hepatic cord showing hepatocytes (green) grooved by canaliculi, fenestrated endothelial cells (purple) lining sinusoids containing erythrocytes (red). Also visible are a Kupffer cell (blue) and a perisinusoidal cell (orange). Collagen fibres (grey) lie in the space of Disse. See **12.151**.

(Rappaport 1969, 1987), is centred on a preterminal branch of an hepatic arteriole and includes the hepatic tissue served by it, bounded by the territories of other acini and by two adjacent central veins (**12.144**). Another proposed subdivision, the *primary hepatic lobule* represents one half of a portal acinus, i.e. a conical volume supplied by a preterminal arteriole, and draining into a single centrilobular vein. These attempts to codify hepatic micro-organization have clarified important problems of liver histopathology, especially the development of zones of anoxic damage, glycogen deposition and removal, and of toxic trauma, which are all related to the direction of arterial flow and thus tend to follow the acinar pattern. There are also real structural and physiological differences within the acinar lobules and they are customarily divided into three zones:

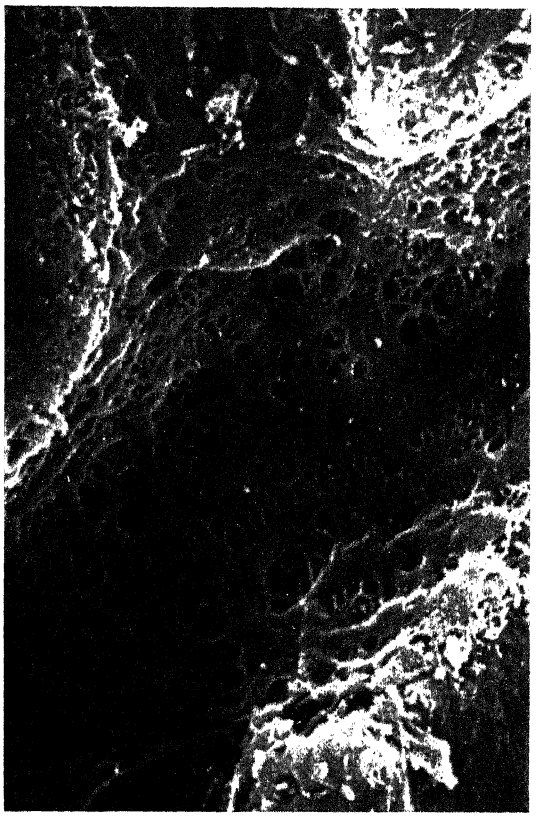
12.149 Electron micrograph showing portions of three adjacent hepatocytes and the intervening bile canaliculi. Magnification × 10 000.



12.150 Transmission electron micrograph of the border of a hepatic sinusoid (sinus.) showing part of an hepatocyte (hep.) and the tenuous fenestrated endothelium (end.) separated by the space of Disse (D) in part of which lies a reticulin bundle (ret.). Magnification × 5000.



12.151 Scanning electron micrograph of the cut surface of the liver (rodent) showing sinusoids with endothelial linings and adjacent hepatocytes, grooved by bile canaliculi (see **12.149**).



12.152 Scanning electron micrograph of the internal surface of a hepatic sinusoid, showing endothelial fenestrations. Magnification x 8000.

- *zone 1* (periportal) i.e. nearest the portal radicles
- *zone 2* further away from these
- *zone 3* around the central venous drainage (see below).

On a larger scale, Rappaport (1969) has proposed the concept of *compound portal acini*, which are more complex groups of hepatic units centred around larger triads.

Cells of the liver (12.146B, C, 147–152)

Cells of the liver include *hepatocytes*, *perisinusoidal (Ito) cells*, *endotheliocytes*, *macrophages* (Kupffer cells), *lymphocytes* (pit cells), the *cells of the biliary tree* (cuboidal to columnar epitheliocytes) and *connective tissue cells* of the capsule and portal tracts. For further details, Bioulac-Sage et al (1991); Jones et al (1991).

Hepatocytes. About 80% of the liver volume and 60% of its cell number are formed by hepatocytes (parenchymal cells). They are polyhedral, with five to twelve sides and are from 20–30 μm across. Their nuclei are spheroidal and euchromatic and often polyploid or multiple (two or more) in each cell (Doljanski 1960). Their cytoplasm typically displays much granular and agranular endoplasmic reticulum, many mitochondria, lysosomes and many well-developed Golgi bodies, features indicating a high metabolic activity. Glycogen granules and lipid vacuoles are usually prominent. Numerous, particularly large peroxisomes and vacuoles containing enzymes such as urease (uricosomes) in distinctive crystalline forms indicate the complex metabolism of these cells. Their role in iron metabolism is shown by storage vacuoles containing crystals of ferritin and haemosiderin.

Hepatocytes also contain characteristic types of cytokeratin (intermediate) filaments which are useful markers in immunohistochemical assessments of pathological tissues (Marceau 1994), allowing them to be distinguished from, e.g. biliary duct cells. Actin microfilaments and microtubules are also quite numerous. Where hepatocytes adjoin bile canaliculi they carry short microvilli and numerous membrane-bound vesicles cluster near the lumen (**12.149**, 151) reflecting the secretion of bile components. The borders of these canaliculi are marked by tight junctions where adjacent hepatocytes lie in contact, preventing their secretions from entering the general intercellular spaces of the liver (and blood plasma from leaking into the biliary tract: the *blood–bile barrier*) and confining them to the canalicular system. The tight junctions are reinforced mechanically by zonulae adherentes (p. 27), anchored into a lamina of actin filaments which surrounds each canaliculus and sends supportive bundles into the short canalicular microvilli. Elsewhere, hepatocytes are linked by numerous gap junctions and desmosomes, although there is free access of blood plasma to the sides of hepatocytes through the intercellular spaces.

On the sides of the cell facing the sinusoids are numerous microvilli, about 0.5 μm long, which create a large area of membrane exposed to the plasma bathing these surfaces (**12.150**).

Hepatocyte structure and metabolism varies within the portal acini, according to their distance from the portal inflow (see above); in zone 1, cells have more mitochondria and granular endoplasmic reticulum, whilst in zone 3 (nearest the central veins) the agranular endoplasmic reticulum is even more extensive, but mitochondria are fewer and more spheroidal. In zone 2, there is a gradient between the other two conditions. Cell size also varies, with a decreasing size gradient from zone 1 to zone 3.

Hepatocytes mediate many metabolic activities. At their sinusoidal interface with blood plasma they release into the bloodstream various plasma proteins which they have synthesized, such as albumins, clotting factors (factor III, fibrinogen) and complement components; they deaminate amino acids by the urea cycle, liberating urea for subsequent renal excretion; convert bilirubin to biliverdin for secretion into bile; they take up and inactivate many endogenous

and exogenous toxic substances from the blood and convert circulating tetra-iodothyronin to the more active tri-iodothyronin. They also store carbohydrates as glycogen, and triglycerides as lipid droplets, metabolizing these as required to release glucose and lipid into the blood. Most lipid thus secreted reaches the perisinusoidal surface of the cell in secretory vesicles, having been conjugated with protein in the endoplasmic reticulum and Golgi apparatus, to form the 'very low density lipoprotein' moiety of blood plasma (Claude 1970), a cholesterol carrier. Iron is stored in the hepatocytes as ferritin granules. In addition, these cells store vitamins of the B complex, including vitamin B_{12}.

At the cell surface facing the bile canaliculus, bile is elaborated and secreted; a major function is the synthesis and secretion of bile salts essential to the emulsification of fats in digestion; the elimination of various toxic materials from the body also occurs via the biliary tree, including some hormones, and a moiety of cholesterol. The liver is also a major route for IgA secretion into the alimentary tract; IgA originates mainly from B lymphocytes in mucosa-associated lymphoid tissue (p. 1442) of the alimentary tract wall; although some is secreted locally via the mucous cells of the gut, much passes into the portal venous system and reaches the liver where it is taken up by hepatocytes and passed into the bile, whence it reaches the alimentary lumen of the duodenum and more distal intestinal regions. All of these metabolic activities generate heat, and the liver is a major source of thermal energy for the maintenance of a high 'resting' body temperature and thus homeothermy.

The multitude of actions performed by hepatocytes is reflected in their structural complexity, which varies with metabolic demand, e.g. agranular endoplasmic reticulum proliferates during barbiturate detoxification (Jones & Fawcett 1966), while in starvation glycogen and lipid reserves disappear. Because of involvement in many such processes, hepatocytes are most vulnerable to anoxia, various toxins and carcinogens, which cause characteristic patterns of degeneration in the portal acini.

Perisinusoidal (Ito) cells. These are much less numerous than hepatocytes. They are irregular in outline, and lie within the hepatic laminae wedged between the bases of hepatocytes. They are typified by numerous lipid vesicles, and by the presence of actin filaments, myosin and the intermediate filament desmin (Johnson et al 1992) indicating that they have many similarities with myofibroblasts (p. 76). These cells have a number of important functions, the most significant being to secrete most of the matrix components of the hepatic laminae including collagens (Friedman et al 1985) and various proteoglycans (e.g. fibronectin). They also store the fat-soluble vitamin A in their lipid vesicles, and are a significant source of growth factors active in the regeneration of the damaged liver, as well as its normal maintenance. Perisinusoidal cells also play a major role in the reorganization of hepatic cords after toxic damage, and pathologically in the replacement of defunct hepatocytes with collagenous fibres, as seen in cirrhosis.

Endotheliocytes. (12.146, 150–152). Hepatic venous sinusoids are generally wider than blood capillaries and are lined by a thin but highly fenestrated endothelium. The endothelial cells are typically flattened, each with a central nucleus and joined to each other by junctional complexes. The fenestrae are grouped in clusters ('sieve plates' 12.152) with a mean diameter of 100 nm, allowing plasma direct access to the bases of hepatocytes. Within the cytoplasm of these cells are numerous typical transcytotic vesicles.

Hepatic macrophages. These cells, also called stellate cells of *von Kupffer*, or more simply, *Kupffer cells*) lie within the sinusoid lumen (12.149, 152), attached to the endothelial surface; these cells, derived from the bone marrow, form a major part of the body's mononuclear phagocyte system (p. 1414), responsible for removing from the circulation much cellular and microbial debris, and secreting various cytokines involved in defence, etc. In the liver they also remove aged and damaged red cells from the circulation (as in the spleen). These cells are irregular, with long processes including lamellipodia extending into the sinusoid lumen; they have flattened nuclei, and their cytoplasm contains characteristic invaginations of the plasma membrane (vermiform bodies). Lysosomes are numerous.

Lymphocytes. Associated with the surfaces of hepatic macrophages are large granular lymphocytes ('pit cells'). These appear to be largely natural killer cells (p. 1405) and are likely to be an important source of defence against viral and other infectious agents.

Hepatic laminae (cords) (12.146–148, 151)

The precise manner in which hepatocytes are arranged in the liver has been much debated. The most recent studies show that in the mature liver, hepatocytes are arranged mainly in plates, one cell thick, of about 20 cells from periphery to centrilobular venule.

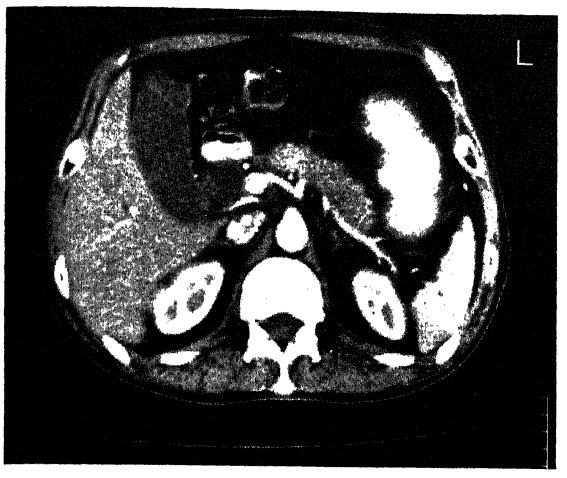
They form a continuous system or *muralium* of *hepatic laminae* (*hepatic cords*) which may branch or anastomose, frequent interlaminar bridges of cells connecting adjacent laminae (12.147). Between the laminae lie *hepatic lacunae* containing endothelium-lined *venous sinusoids*, which anastomose with each other via gaps in the hepatic laminae. Where hepatocytes adjoin portal canals or hepatic venous tributaries they form a *limiting plate*, surrounding the vessels and perforated by their radicles and by rami of the hepatic artery and biliary ductules; a similar limiting plate composed of a single layer of liver cells underlies the entire capsule of the liver. In histological sections (12.145, 146) the rows of liver cells seen radiating from the central vein to the lobular periphery are really sections through hepatic laminae. These rows, with intervening sinusoids, do not pass straight to the periphery like the spokes of a wheel but run irregularly, because the laminae themselves are irregular and branched (12.147).

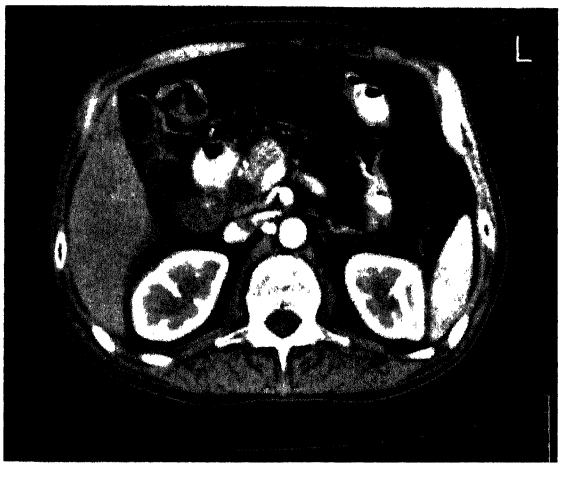
Sinusoids are fed at one end with blood from fine branches of the hepatic portal venules (inlet venules) and hepatic arterioles, which pass through the limiting plate of hepatocytes to enter a hepatic lobule (12.147). Blood from these sources percolates between the walls of the sinusoids to the central veins and is exposed to the activities of the cells around the sinusoids. The endothelial linings of the sinusoids are separated from hepatocytes of the hepatic laminae by a narrow gap, the *perisinusoidal space of Disse* (12.150, 151) which is normally about 0.2–0.5 μm wide, but distends in anoxic conditions: it contains fine collagen fibres (chiefly type III, with some types I and IV), the irregular microvilli of adjacent hepatocytes and occasional non-myelinated nerve terminals (Forssmann & Ito 1977). This space is continuous at the lobular periphery with the *space of Mall* surrounding the vessels and ductules in the portal canals. In the latter space, lymph vessels begin as culde-sac capillaries, as elsewhere; only a very few reach the periphery of the lobule. As already mentioned hepatic perisinusoidal cells (Ito cells) are also present in small numbers in the space of Disse. Central veins from adjacent lobules form *interlobular veins*, which unite as *hepatic veins*, draining blood to the inferior vena cava.

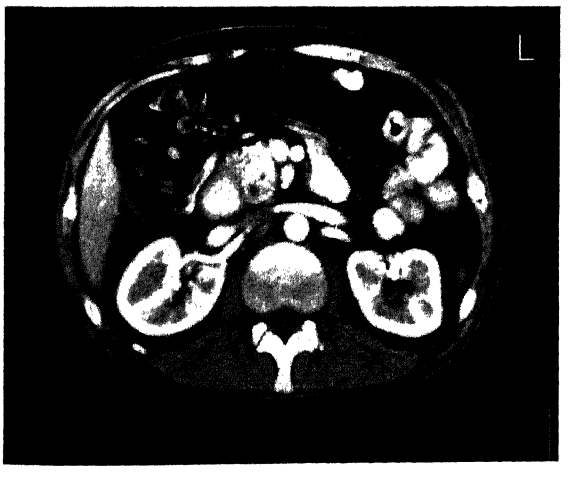
Minute *bile canaliculi* (12.147–149, 151) form nets with polygonal meshes in the hepatic lobules; each hepatocyte is surrounded by canaliculi except on its juxtasinusoidal sides. Hepatic laminae thus enclose a network of canaliculi which pass to the lobular periphery where they join to form narrow intralobular ductules (*terminal ductules* or the *canals of Hering*) lined by squamous cuboidal epithelium; these exit through the terminal laminae to enter interlobular hepatic ductules in the portal canals. Intralobular ductules differ from the other biliary canals in their structure and reaction to injury; e.g. they proliferate when the flow of bile is obstructed outside the liver (Biava 1964b; Jones et al 1975). Hepatic ductules in portal canals are lined by cuboidal or columnar cells which may contain cholesterol crystals and lipid droplets.

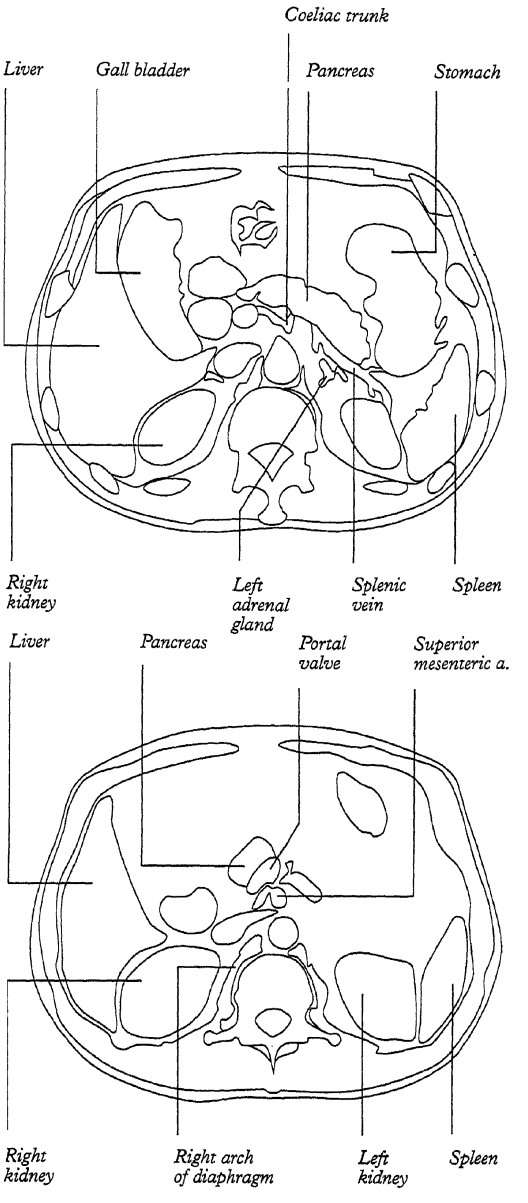
Preterminal hepatic arterioles in the portal canals branch to convey arterial blood to the sinusoids by several routes, the chief being via a fine capillary plexus around the interlobular ductules and ducts which drains to branches of the portal veins, inlet venules and hepatic sinusoids. Some arterial blood passes directly to the hepatic sinusoids, bypassing these capillary plexuses; but this is apparently only a small part of the total flow (Burkel 1970; Healey 1970). Sinusoids thus contain mixed venous and arterial blood to sustain their cells. The composition, volume and velocity of blood through any local region may be regulated according to changing needs by the sphincters around the entry points of inlet venules and hepatic arterioles, and by the contractile walls of the sinusoids. Each portal triad supplies a distinct territory; normally there are no anastomoses between territories. Hepatic veins run quite separately with respect to the triadic system, freely crossing the boundaries of triadic territories.

Haemopoiesis in the liver. The fetal liver is a major haemopoietic organ, erythrocytes, leucocytes and platelets developing from the mesenchyme covering the sinusoidal endothelium (p. 1407).









12.153A, B, C Transverse section of abdomen at level of: A coeliac trunk; B superior mesenteric artery and portal vein; C head of uncinate process of pancreas and left renal vein. CT scans provided by J. Dussek, Dept of Surgery, Guy's Hospital, London. Photographed by Sarah Smith, Division of Anatomy, Guy's Hospital, London.

CLINICAL ANATOMY OF THE LIVER

On account of its large size, fixed position, and friability, the liver is sometimes ruptured; haemorrhage may be severe, because the hepatic veins lie in rigid canals and are unable to contract. The organ may be torn by a broken rib, perforating the diaphragm. Clinical evidence suggests that the bloodstreams of the superior mesenteric and splenic veins remain largely separate in the portal vein, passing respectively along the right and left portal branches to the right and left physiological (vascular) lobes (p. 1797); thus malignant or infective emboli may be more pronounced in the right lobe if the primary disease is in the territory drained by the superior mesenteric vein, or in the left if it is in the splenic or inferior mesenteric territory. This correlation is also supported in experiments in living animals. Vascular hepatic segmentation (p. 1798) is a vital factor in *partial hepatectomy*.

The liver and its related structures are clearly visible in MRI images (**12**.153A–C), which are valuable in diagnosis of hepatic pathology.

Liver transplantation has grown from a largely experimental procedure, first carried out 30 years ago, to a well-established treatment option for patients with advanced liver disease. Foster, in his review of liver surgery in 1991 stated, 'Total hepatectomy with liver transplantation may be the most difficult operation ever devised, both technically and physiologically.' In 1992, over 500 liver transplantations were carried out in the United Kingdom, and over 2000 in more than 70 centres in Europe, with over three-quarters of patients making a full recovery.

Complete knowledge of surgical anatomy related to the liver is essential for both the donor harvesting operation and the recipient operation. The shortage of paediatric donors has resulted in the rapid development of innovative surgical techniques where adult donor grafts are reduced in size to two or four segments to implant into children, further emphasizing the contributions by Couinaud and Hjortsjö, who were among the first to describe the segmental anatomy of the liver (see p. 1797).

DONOR LIVER REMOVAL

The conventional textbook description of a single hepatic artery arising from the coeliac trunk is seen in only 60–65% of cases, with anatomical variations being present in over one-third of cases. The commonest variations are a replaced or accessory left hepatic artery from the left gastric artery (20%), and a replaced or accessory right hepatic artery arising from the superior mesenteric artery (15%), running posterior to the common bile duct. Occasionally both variants may be present together (5%), or the entire hepatic arterial supply may be derived from the superior mesenteric artery or from a common coeliacomesenteric trunk. Identification of the arterial supply is essential prior to perfusion to cool and preserve the donor organs. To remove the liver from the donor, the common bile duct is divided just above the pancreas, the gallbladder incised and the bile flushed out prior to cooling, to prevent bile-induced epithelial injury. After cross-clamping the aorta above the level of the coeliac axis, cooling of the liver is achieved by portal venous and aortic perfusion with University of Wisconsin solution (UW) at 4°C. The liver retrieval is completed, preserving an adequate length of inferior vena cava (IVC), the coeliac trunk with an aortic patch, and a suitable length of portal vein. In addition, the common and external iliac arteries and veins are retrieved in the event that a vascular reconstruction is necessary, e.g. because of portal vein thrombosis, or arterial vascular reconstruction. The graft is then preserved for up to 18 hours in UW at a temperature between 0–4°C.

RECIPIENT OPERATION

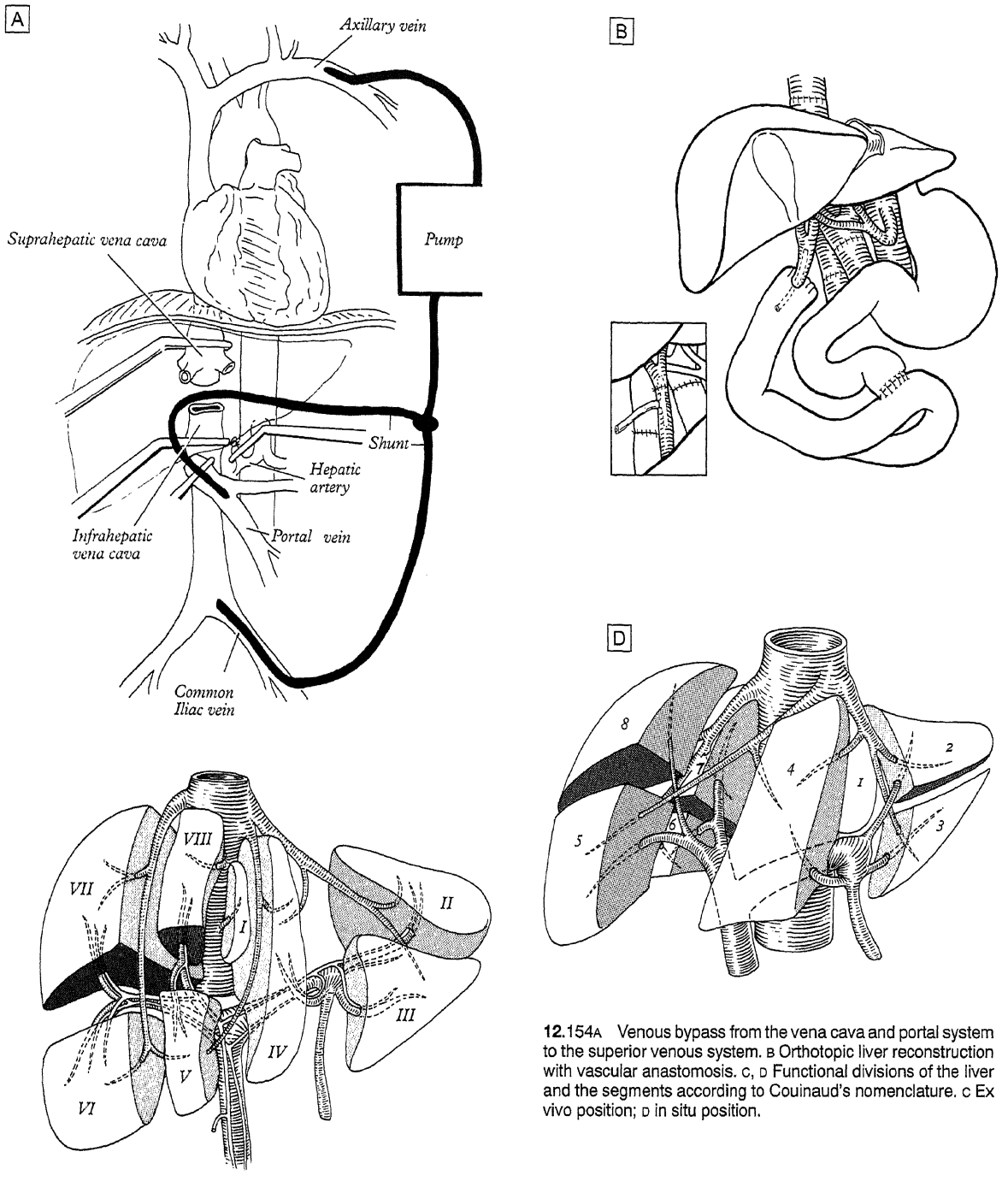
The use of UW has permitted safe prolonged storage times, so that this operation is usually performed as a semi-elective procedure during the day. The removal of the recipient's diseased liver is usually undertaken in the presence of portal hypertension, often with previous biliary or portal surgery, and occasionally with additional technical problems such as portal vein thrombosis or extensive varices. The structures in the porta hepatis are systematically divided close to the liver hilum, the hepatic artery, the common hepatic duct and the portal vein. Most centres make use of a venovenous bypass in adults during the anhepatic phase, where blood is pumped from the portal and femoral vein to the axillary vein (**12**.154A); its advantages include decompression of the clamped IVC and portal system, providing adequate circulating blood volume and venous return, thereby allowing for a more controlled anhepatic phase.

Next, the IVC is identified below the liver and the left and right triangular ligaments are divided and the bare area of the liver is dissected off the diaphragm. The suprahepatic IVC is then dissected and encircled. The hepatectomy is completed after placing supra- and infrahepatic IVC clamps. An alternative technique called the 'piggy-back' technique leaves the entire recipient IVC in place, with ligation of the individual short hepatic veins, particularly from the caudate lobe.

After achieving full control of bleeding, the new liver, which has been dissected and prepared on a sterile trolley, is implanted into the recipient: the upper IVC anastomosis first, the lower IVC next followed by the portal vein using a continuous vascular suture (**12**.154B). The UW within the liver vessels is next washed out. The graft is then reperfused with blood via the portal vein. The arterial anastomosis is usually made between the donor and recipient common hepatic arteries. In the event of a donor left hepatic artery from the left gastric, no reconstruction is necessary, the coeliac trunk being used for the anastomosis. A donor right hepatic artery arising from the superior mesenteric artery requires some additional reconstruction, most commonly this is anastomosed to the donor splenic artery stump. Not infrequently, especially in patients undergoing retransplantation for hepatic artery thrombosis, it is often impossible to achieve an adequate arterial inflow from the coeliac trunk, and a donor iliac artery aortic conduit is constructed from the recipient infrarenal aorta to the donor hepatic artery. Portal vein thrombosis is no longer a contraindication to liver transplantation, and successful portal revascularization can be obtained by thrombectomy, dissection posterior to the pancreas down to healthy portal vein, use of large collaterals, e.g. left gastric vein, or by means of a donor iliac vein graft from the recipient superior mesenteric vein to the donor portal vein.

REDUCED-SIZE LIVER TRANSPLANTATION

The majority of children with liver disease present this condition in infancy and early childhood. It is in this group that there is a great shortage of donor organs. Over the past decade, many groups have shown that it is safe to implant reduced-size grafts, with a reduction in waiting time, fewer deaths on waiting lists, and with no increase in complications related to the reduction process. These techniques allow a donor–recipient weight discrepancy of up to 10:1, when only segments 2 and 3 are transplanted (**12**.154B). The back-table reduction operation entails a meticulous hilar and intrahepatic vascular and biliary dissection, dissection of the left hepatic vein, and the parenchymal resection just to the right of the falciform ligament. In

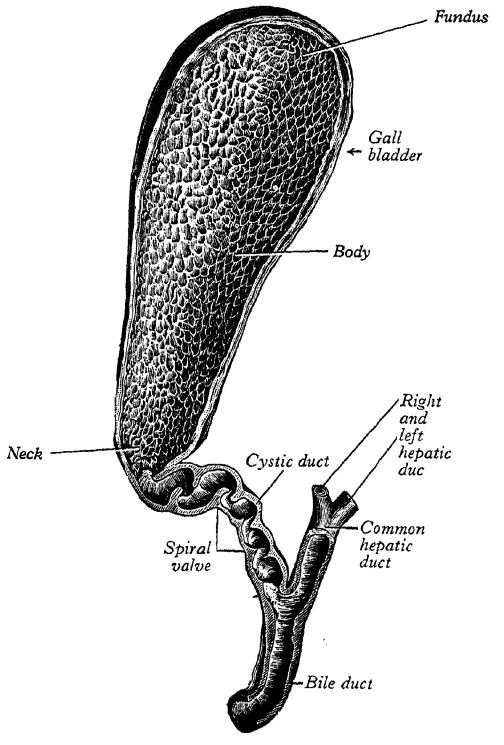


12.154A Venous bypass from the vena cava and portal system to the superior venous system. B Orthotopic liver reconstruction with vascular anastomosis. C, D Functional divisions of the liver and the segments according to Couinaud's nomenclature. C Ex vivo position; D in situ position.

larger children, or when the discrepancy is less than 4:1, the right lobe (segments 5–8) may be utilized.

The splitting of a single donor liver into right and left lobes, thus benefiting two recipients, is also an established procedure, where the vessels to one of the halves have to be lengthened using donor vessels. A few centres have gone one step further, in an effort to further reduce the waiting period, to partial transplants from living relations, where segments 2 and 3 of a parent's liver are transplanted into a child. Over 100 such transplants have been performed worldwide, particularly in the United States of America and Japan, with low donor morbidity and excellent short and long term results.

In conclusion, liver transplantation has developed into a major effort to support patients with advanced liver disease. Although the techniques have been standardized, it remains a difficult and complex procedure. A complete knowledge of the anatomic variations in arterial supply, bile duct, portal and hepatic venous anatomy, as well as the segmental anatomy of the liver, is an essential prerequisite to developing the surgical skills for this form of surgery.

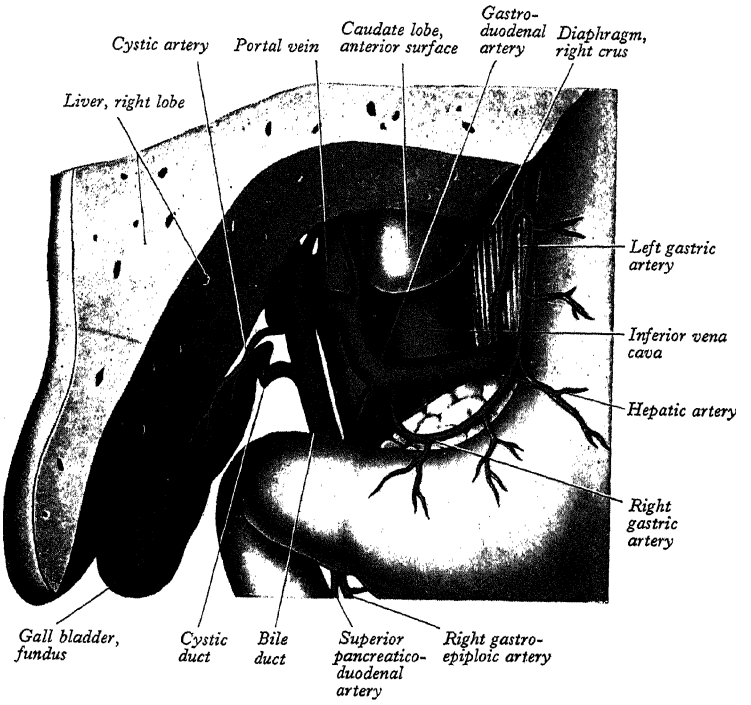


12.155 Interior of the gallbladder and bile ducts.

BILIARY DUCTS AND GALLBLADDER

The hepatic ductual apparatus consists of:

- the *common hepatic duct*, formed by the junction of the *right* and *left hepatic ducts*
- the *gallbladder*, a reservoir for bile



12.156 Dissection to show the relations of the hepatic artery, bile duct and portal vein to each other in the lesser omentum: anterior aspect.

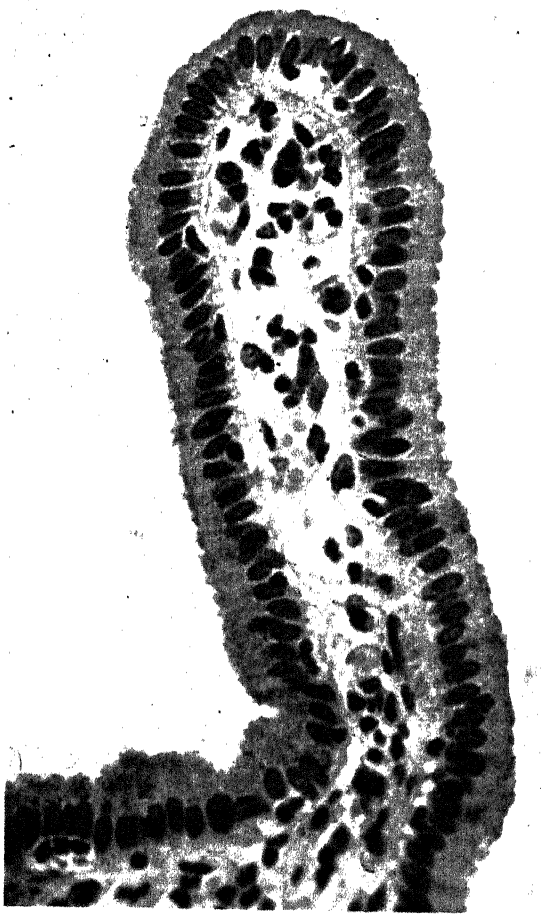
- the *cystic duct* of the gallbladder
- the *bile duct*, formed by the junction of the common hepatic and cystic ducts.

COMMON HEPATIC DUCT (12.155, 156)

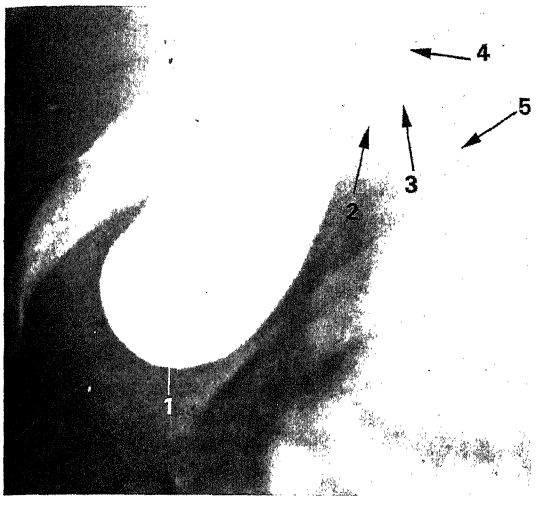
The main right and left hepatic ducts issue from the liver and unite near the right end of the porta hepatis as the common hepatic duct, which descends about 3 cm before being joined on its right at an acute angle by the cystic duct to form the main bile duct. The common hepatic duct lies to the right of the hepatic artery and anterior to the portal vein.

GALLBLADDER

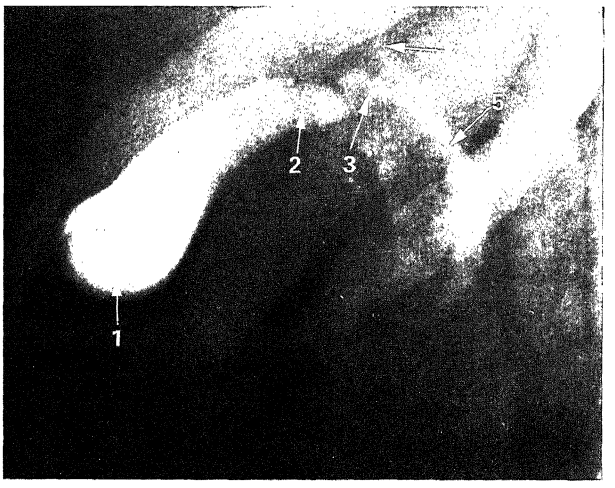
The gallbladder (**12**.140, 141, 144, 155–160) is a slate-blue, piriform sac partly sunk in a fossa in the right hepatic lobe's inferior surface. It extends forwards from a point near the right end of the porta hepatis to the inferior hepatic border. Its upper surface is attached to the liver by connective tissue; elsewhere it is completely covered by peritoneum continued from the hepatic surface. Occasionally it is completely invested by peritoneum and even connected to the liver by a short mesentery. It is 7–10 cm long, 3 cm broad at its widest and 30–50 ml in capacity. It is described as having a fundus, body and neck. The *fundus*, the expanded end, projects down, forwards and to the right, extending beyond the inferior border to contact the anterior abdominal wall behind the ninth right costal cartilage, where the lateral edge of the right rectus abdominis crosses the costal margin. Posteriorly it is related to the transverse colon, near its commencement. (These relations change when the gallbladder is lower, as it often is in slender females, see Fleischner & Sayegh 1958.) The *body* is directed up, back and to the left; near the right



12.157 Section through a surface projection (ruga) of the gallbladder showing the columnar epithelial cells and lamina propria. Haematoxylin and eosin. Magnification × 500.



12.158 Anteroposterior radiograph of the gallbladder and biliary ducts after the oral administration of sodium tetra-iodophenolphthalein the previous day.



12.159 The same field as 12.158 but taken 20 minutes after a fatty meal, demonstrating the contraction and partial emptying of the gallbladder. In both A and B: (1) fundus of gallbladder; (2) neck of gallbladder; (3) cystic duct; (4) common hepatic duct; (5) the bile duct.

end of the porta it is continuous with the gallbladder neck. It is related above to the liver, below to the transverse colon and, further back, to the first and upper end of the second segments of the duodenum. The *neck* (cervix) is narrow, curving up and forwards and then abruptly back and downwards, to become the cystic duct, at which transition there is a constriction. The neck is attached to the liver by loose connective tissue containing the cystic artery. The mucosa of the neck is obliquely ridged, forming a spiral valve; when the neck is distended, this gives its surface a spiral groove. From the right side of the neck a small recess may project down and back towards the duodenum. Often termed Hartmann's pouch (but originally described by Broca), it has been widely regarded as a constant feature, but Davies and Harding (1942) have shown that it is always a sequela of pathological states, especially dilatation; when it is large the cystic duct arises from its upper left aspect and not from what appears to be the gallbladder's apex.

(12.155, 156, 158, 159)

This structure is 3–4 cm long; it passes back, down and to the left from the neck of the gallbladder, joining the common hepatic duct to form the bile duct. It is adherent to the common hepatic duct for a short distance before joining it, usually near the porta hepatis but sometimes lower, in which case the cystic duct lies along the lesser omentum's right edge. Its mucosa bears five to 12 crescentic folds, like those in the gallbladder's neck. They project obliquely in regular succession, appearing like a *spiral valve* (12.155). When the duct is distended, the spaces between the folds dilate and externally it appears twisted like the neck of the gallbladder.

BILE DUCT (12.155, 156, 158, 159).

The bile duct is formed near the porta hepatis, by the junction of the cystic and common hepatic ducts; it is usually about 7.5 cm long and 6 mm in diameter (see below). It descends posteriorly and slightly to the left, anterior to the epiploic foramen, at the right border of the lesser omentum, in front and to the right of the portal vein and to the right of the hepatic artery proper (12.156). It passes behind the first (superior) part of the duodenum, with the gastroduodenal artery on its left, and then runs in a groove on the superolateral part of the posterior surface of the head of the pancreas (12.133), anterior to the inferior vena cava and sometimes embedded in pancreatic tissue (p. 1790). Lytle (1959) has shown that the duct may be close to the left aspect of the second (descending) part of the duodenum or as much as 2 cm from it and that, even when it is embedded in pancreas, a superficial groove marking its position can be palpated behind the descending part of the duodenum, stones in the duct being thus detected. Left of the descending part of the duodenum the bile duct reaches the pancreatic duct; together they enter the duodenal wall where they usually unite to form the *hepatopancreatic ampulla* (p. 1791), the distal, constricted end of which opens into the descending part of the duodenum on the summit of the major duodenal papilla (12.99, 134), about 8–10 cm from the pylorus (p. 1763). The position of the bile duct is indicated on the anterior abdominal surface by a line starting 5 cm above the transpyloric plane and 2 cm right of the median plane and descending vertically for 7.5 cm.

VESSELS

The *cystic artery* is described on page 1550 and the *cystic veins* on page 1604. The lower part of the bile duct receives rami from the *posterior superior pancreaticoduodenal artery* (p. 1549), while its upper part and the hepatic ducts receive rami from the cystic artery. The *right hepatic artery* supplies its intermediate part through very small rami, the main supply being from the cystic and posterior superior pancreaticoduodenal arteries. These supplies vary (Shapiro & Robillard 1948; Michels 1962). The posterior superior pancreaticoduodenal artery anastomoses with the posterior branch of the inferior pancreaticoduodenal near the hepatopancreatic ampulla; where this anastomosis is poor, ligation of the posterior superior pancreaticoduodenal artery may result in gangrene or stricture of the bile duct (Henley 1955). *Veins* from the upper part of the bile duct and hepatic ducts and from the gallbladder and cystic duct usually enter the liver, while those from the lower part of the bile duct enter the portal vein. *Lymph vessels* of the gallbladder and bile ducts are described on page 1619. Sympathetic and parasympathetic *innervation* is from the coeliac plexus along the hepatic artery and its branches. Autonomic plexuses exist in the muscular and submucous layers, and ganglion cells, presumably parasympathetic, have been demonstrated in these plexuses in monkeys (Sutherland 1966, 1967). Fibres from the right phrenic nerve, through communications between the phrenic and coeliac plexuses, appear to reach the gallbladder via the hepatic plexus, thus explaining referred 'shoulder pain' in gallbladder pathology.

VARIATIONS IN GALLBLADDER AND BILE DUCTS

The gallbladder varies in size and shape; in rare cases it is duplicated (Mincsev 1967), with two or combined cystic ducts, or is absent, though its duct may be present. The junction of the cystic and common hepatic ducts varies in its level from the porta hepatis to behind or even below the duodenum's first (superior) part; when the junction is low, the two ducts may be connected by fibrous tissue and in cholecystectomy clamping the cystic duct without injuring the common hepatic (or main bile) duct is difficult. Occasionally the cystic duct joins the right hepatic duct; it may pass behind or in front of the common hepatic duct, joining it on its left surface.

Accessory hepatic ducts may emerge, more often from the right lobe, to join the main hepatic ducts or, rarely, the gallbladder itself. Failure of canalization of bile ducts during development leads to a rare congenital atresia or stenosis with rapidly fatal results. The bile and pancreatic ducts may open separately into the duodenum or join even before entering its wall. Variations of the ductual arteries are much more common (p. 1549). For further information consult Santulli and Blanc (1961), Boyden et al (1967).

MICROSTRUCTURE OF THE GALLBLADDER AND BILIARY DUCTS (12.157)

The gallbladder's wall has serous, fibromuscular and mucous layers. The *serosa* completely covers the fundus but only coats the inferior surfaces and sides of the body and neck of the gallbladder; beneath it is subserous loose connective and adipose peritoneal tissue. The *fibromuscular layer* is composed of fibrous tissue mixed with smooth muscle cells arranged loosely in longitudinal, circular and oblique bundles. Internally, the *mucosa* is loosely connected with the fibrous layer, is generally yellowish-brown and elevated into minute rugae with a honeycomb appearance (**12.**155). Its epithelium is a single layer of columnar cells which vary with species. Electron microscopy (Chapman et al 1966) in dogs shows microvilli on their apical surface, irregularly arranged, with endocytic or pinocytotic vesicles between their bases. Basally, spaces between epithelial cells are dilated and many capillaries adjoin the basement membrane. These features indicate active absorption of water and solutes from the bile to concentrate it. Basal spaces are large during absorption of water (Kaye et al 1966). Biliary concentration appears to involve the active transport of sodium and calcium, making an osmotic gradient from the lumen of the gallbladder to the capillaries of the lamina propria. In the apical parts of some cells, particularly those near the ducts, mucous granules appear; they are secreted into the lumen (Johnson et al 1962; Mueller et al 1972).

The large biliary ducts have external fibrous and internal mucous layers. The former is fibrous connective tissue with a few longitudinal, oblique and circular smooth muscle cells. (Muscle cells appeared in only 12 of 100 human common bile ducts examined by Mahour et al 1967.) The mucosa is continuous with that of the hepatic ducts, gallbladder and duodenum; like theirs, its epithelium is columnar; many lobulated mucous glands occur in the wall of these ducts. In the bile duct are many tubulo-alveolar glands arranged in clusters, secreting mucin, some at least of which is sulphated (McMinn & Kugler 1961). Electron microscopy of the bile duct epithelium in guinea-pigs showed microvilli on its luminal surfaces. Secretory granules, some of mucinogen, appear in the apical cytoplasm. Epithelial cells in rats, which lack a gallbladder, are termed either light or dark according to their electron density; light cells have longer, more regular microvilli but the basal intercellular spaces between adjacent dark cells are larger; the mucosa appears to modify bile, compensating for the absent gallbladder (Riches & Palfrey 1966).

Circular muscle around the lower part of the main bile duct, including the ampulla and terminal pancreatic duct, forms the *sphincter of the hepatopancreatic ampulla* (*sphincter of Oddi*), comprising muscle at three levels:

- at the end of the bile duct (*sphincter ductus choledoci*)
- at the end of the pancreatic duct (*sphincter ductus pancreatici*)
- around the ampulla.

Only the muscle at the end of the bile duct is constant. Expulsion of gallbladder contents appears to be under hormonal control. Fat or acid in the duodenum probably causes the liberation of CCK, stimulating the gallbladder to contract. Muscle cells in its wall have surface receptors for this hormone, which can therefore stimulate them to contract directly. In any case, when storage pressure exceeds 100 mm of bile, the gallbladder contracts, the sphincter of Oddi relaxes and bile enters the duodenum. Kirk (1944) denied the presence of sphincteric musculature around the openings of the bile and pancreatic ducts, describing the sphincter of Oddi as submucosal and continuous with the circular muscle of the duodenum. However, subsequent studies suggest that in man and other primates a common sphincter surrounds both ducts and that the common bile duct has a second sphincter as described above (Boyden 1957, 1966). The termination of the united bile and pancreatic ducts is packed with villous, valvular folds of mucosa and muscle cells enter their connective tissue cores. This suggests that contraction results in retraction and clumping of the folds, preventing reflux of duodenal contents and controlling the exit of bile. In cats stimulation of vagal rami to this region relaxes the biliary opening; the human *myenteric* (*Auerbach's*) *plexus* is well developed at the ends of the ducts. Inflammatory swelling of villous folds may obstruct them.

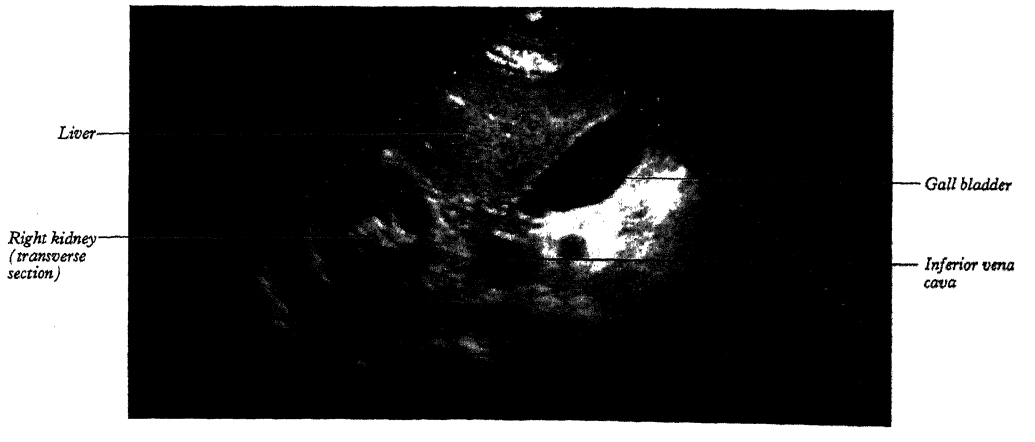
CLINICAL ANATOMY OF THE GALLBLADDER

The gallbladder may be distended by calculi or by obstruction of the cystic duct and may project down and forwards towards the umbilicus. It moves with respiration. Obstruction of the bile duct, apart from lithiasis, is often due to pressure of malignant tumours, especially in the pylorus or pancreas. It also follows cicatricial contraction after ulceration in the duct. Enormous distension of the bile duct and its radicles may also occur.

Cholecystography (12.158, 159)

The gallbladder is not radio-opaque, but radio-opaque substances introduced into the bloodstream are excreted by the liver into bile, and concentration in the gallbladder renders it much more strongly radio-opaque. The form, position and emptying of the gallbladder can be demonstrated by radiographs; its position and form vary with the general build of the body (or somatotype; Davies 1927); in broad (hypersthenic) types it is wide, high up and placed far laterally (at the level of the first lumbar vertebra), whereas in narrow (asthenic) types it is narrow, more medial and may reach as low as the fourth lumbar vertebral level.

The gallbladder is also clearly visible in ultrasonograms (**12.**160).



12.160 Transverse ultrasound sector scan of the abdomen to show the gallbladder and right kidney. (Supplied by Shaun Gallagher, Guy's Hospital; photography by Sarah Smith, UMDS, Guy's Hospital Campus, London.)